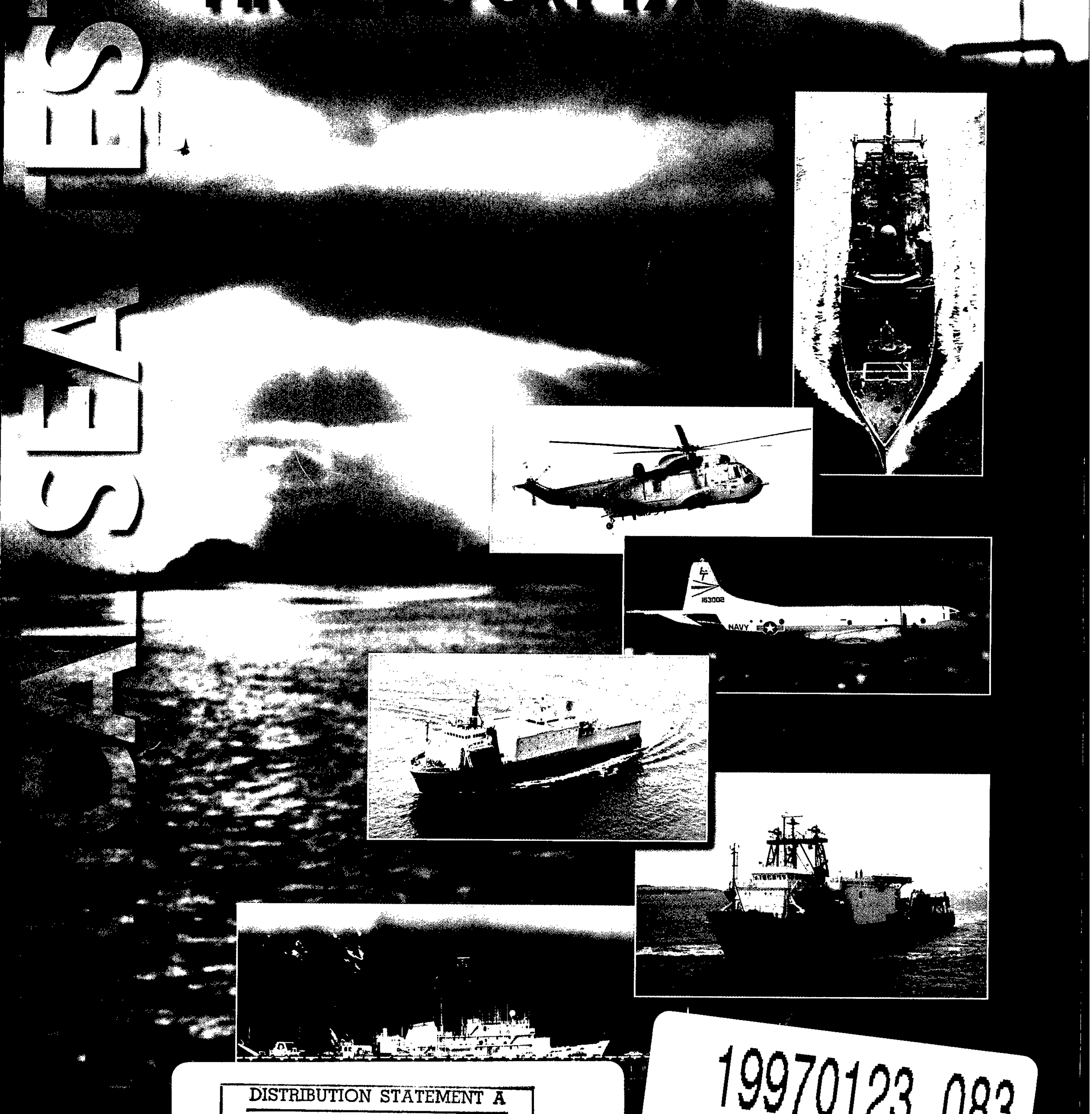
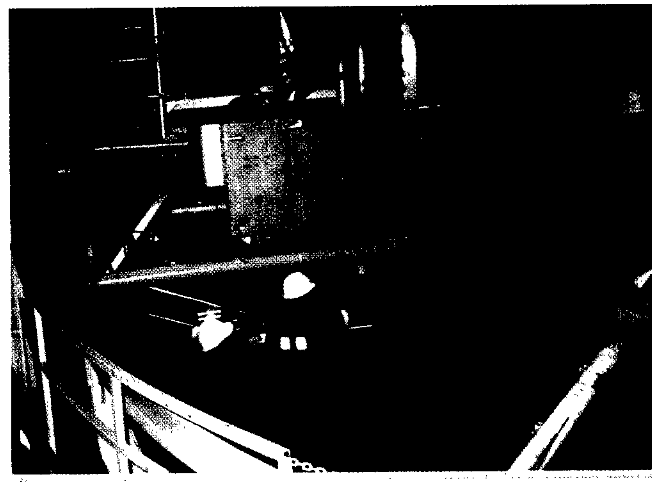
CRITICAL SEA TEST

FINAL REPORT 1996





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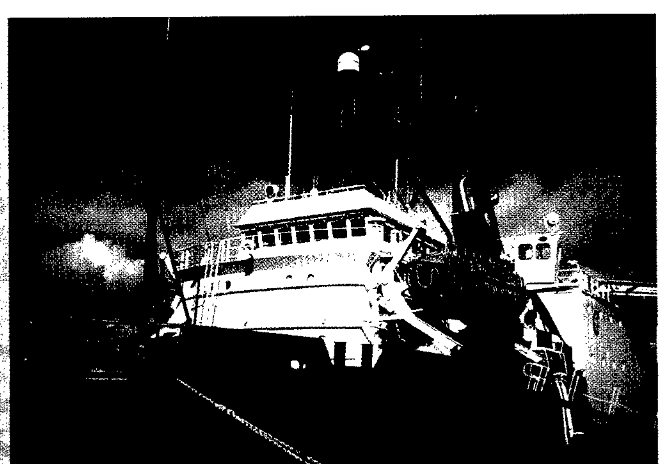
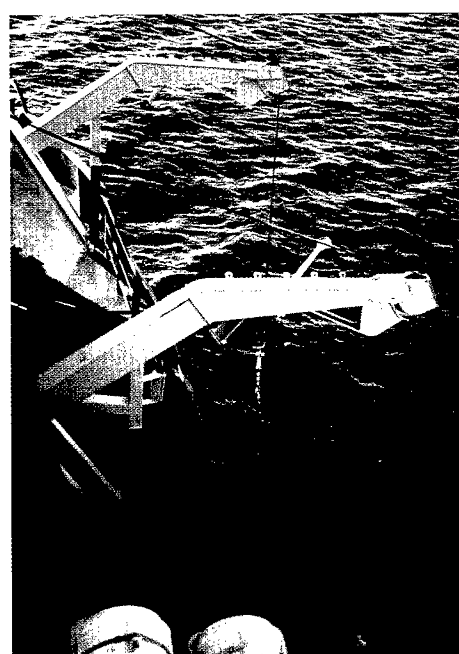




Foreword

In 1996, the Critical Sea Test (CST) Program completes a ten-year history of contributions to the use of Low-Frequency Active Acoustics (LFAA) in Undersea Warfare. The CST Program originated in Fiscal Year 1987 as a CNO Urgent Antisubmarine Warfare (ASW) Research and Development (R&D) Program (CUARP) initiative to counter the growing capability of the Soviet Navy to develop ever-quieter submarines. The program was initiated by the Space and Naval Warfare Systems Command to develop timely answers to key scientific and design issues related to the development and effective deployment of LFAA detection systems.

By design, CST has been an experimentally focused program providing broad-based support to the full variety of developing LFAA systems within the air tactical, submarine tactical, surface tactical, and surveillance communities. To provide such support, CST has executed research thrusts in both Science and Technology and Undersea Warfare.

In this report, three basic aspects of CST's efforts are discussed. First, as an experimental program, CST has of necessity developed a number of experimental capabilities and measurement techniques. Those techniques, which have proven to be of continuing value to both the research and data acquisition (survey) communities, are summarized in this report. Second, the basic science and technology contributions of the CST Program in areas of 1) environmental acoustics and system performance prediction and 2) LFAA signal and information processing are reviewed. Third, the implications of those results for Undersea Warfare are reviewed, with regard to both enhancement of individual system development and the larger arena of multiple systems coordination for Acoustic Warfare operations.

The Critical Sea Test Program has provided valuable and lasting contributions to the LFAA community. Its technology results, its demonstrations of capability, and last but certainly not least, the expertise of its team members represent the cutting edge of LFAA technology development today.

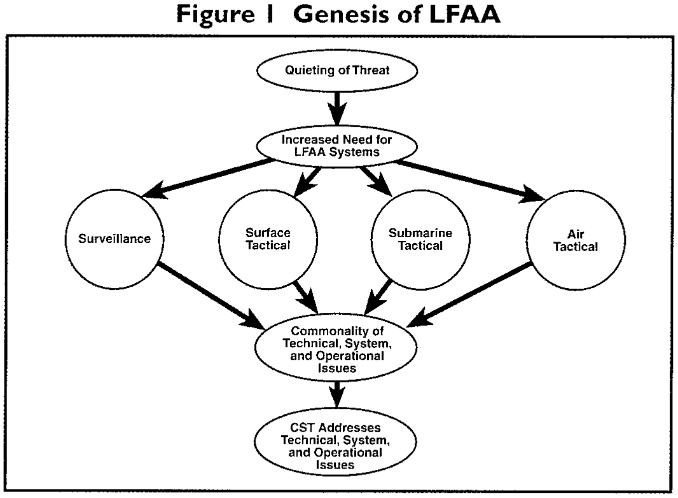
CONTENTS

Introduction

The origins of the Critical Sea Test Program can be traced directly to the quieting of the Soviet SSN force. With improvements in the performance and stealth of these platforms, increased interest in the utility of active acoustic systems for surveillance applications developed within the U.S. Navy. To meet the quieter Soviet threat, the Navy initiated a wide spectrum of programs ranging from development of a new low-frequency tactical system (AN/SQQ-89I) to investigation of the activation of existing fixed surveillance systems [e.g., the Sonar Surveillance System (SOSUS)] and mobile surveillance systems [e.g., the Surveillance Towed Array Sensor System (SURTASS)]. While earlier programs (Artemis, Diana, Standard Aura, Active Adjunct for Undersea Surveillance, and Fixed-Fixed are a few) had addressed discrete aspects of, or discrete concepts for, active acoustic surveillance, the CST Program was established as a broad-based program to provide technology support to all such programs.

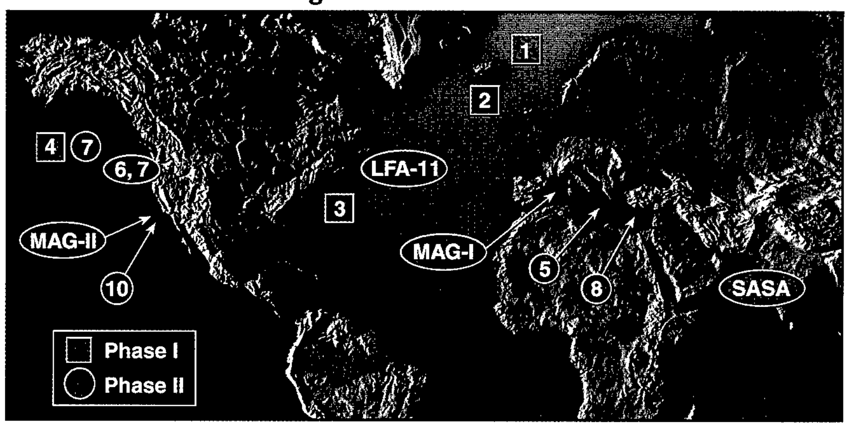
By its charter, the CST Program was tasked to work across a broader frequency range (50 to 1000 Hz) than had the predecessor programs mentioned above. Further, CST researched the utility of both monostatic and bistatic concepts, supported developing understanding of database requirements to support Low-Frequency Active Acoustics (LFAA) operations, and worked to resolve the underlying technical issues that had limited the development of all of the various nascent LFAA systems. These efforts were based upon a recognition of the commonality of the underlying technology issues for a variety of system concepts, and the economies that could be achieved by addressing these issues in a single umbrella program (Figure 1).

Figure 1 Genesis of LFAA



The CST Program was conducted in two phases. Phase I, conducted from 1987 through 1990, consisted of a sequence of four field tests concentrating on fundamental technology issues associated with deep-ocean operation of LFAA systems. Beginning in Fiscal Year 1991, Phase II of the CST Program reflected a response to the changing world political climate, which increased the urgency associated with resolution of issues impeding use of LFAA systems in Third-World arenas or in limited-intensity conflicts. Further, at that time, LFAA technology had matured sufficiently to allow consideration of questions related to the effective *utilization* of such systems (so-called "Acoustic Warfare" issues). Phase II consisted of a sequence of nine at-sea evolutions. The locations of the various Phase I and Phase II sea trials are shown in Figure 2.

Figure 2 CST Locations



Throughout its history, the CST Program has provided products targeted at a wide range of other programs. Figure 3 shows the variety of programs identified for support midway through the program, at the outset of Phase II. More recently, CST products have continued to transition to support development programs throughout the air, submarine, surface, and surveillance communities. Figure 4 samples the variety of products identified for transitioning to the LFAA systems-development community. CST results will provide a heritage that will assist future developments in areas such as system performance upgrades, survey requirements and database development, environmentally adaptive systems, tactical decision aids, data fusion and connectivity, and advanced concept development.

Figure 3 Development Programs Sharing Common Issues with CST

● = High Priority; ■ = Moderate Priority

	System			Scientific						Acoustic Warfare			
	Source Effects	Wave/ Proc.	Perf. Anal.	Surf. Scat.	Bott. Scatt.	Vol. Scat.	Dist. Reverb.	Tgt. Str.	Prop-agation	Inter-operability	Integrated ASW/Data Fusion	CM/ CCM	Decision Aids/ Models
Systems													
AN/SQQ-89I	■	●	●	●	■	●	●	●	■	●		●	●
MSS	■	●	●	●	●	●	●	●	■			●	●
Air Tactical	●	●	●	●	●	●	■	■	●		■	●	●
LFA	■	●	●	■	●		●	●	■	●	■	●	●
ADI	■	●	●	■	●	■	●	●	■	■	●	●	●
Fixed Systems	●	●	●	■	●		■	●	■	●	■	●	●
Submarine Security	■	●	●	■	■	■	●	●	■	●	●	●	●
Concepts & Tactics													
Submarine Security	■	●	●	■	■	■	●	●	■	●	●	●	●
Surface Warfare Development Group			●				■	■	■	●	●	●	●
SUBDEVRON 12			●				■	■	■	●	●	●	●

CST Phase I History

The Phase I Program Plan for CST identified the following five fundamental facets of the basic approach for execution of the program:

- Identify science issues.
- Deploy an at-sea test platform.
- Execute a multi-year test program.
- Assess bistatic system concepts.
- Perform quick-turnaround analyses.

Science issues identified for exploration by the program fell into the categories of reverberation, target strength, signal processing, propagation and forward scatter, performance prediction, and system design trade-offs. A sequence of four field tests was conducted. The selection of sites was specifically designed to address the full range of acoustic environments of concern for the deep-water threat of the time.

When Phase I of CST began in 1987, numerous systems-development programs were identified that could directly benefit from the efforts of such a program. Surveillance systems supported by CST included the LFA SURTASS Program exploring the activation of SURTASS, and other surveillance efforts exploring the potential for activation of fixed receivers. Numerous tactical air systems such as ADAR, AAS, and AAA were supported by CST. The Air-Deployed Acoustic Receiver (ADAR) was a multistatic receiver being developed for use in concert with LFAA sources for Battle Group protection. The Air Active Sonobuoy (AAS) was a replacement for the Directional Command-Activated Sonobuoy System (DICASS), operating in the 50-to-3000-Hz range. The Air Active Adjunct (AAA) was to be a multistatic system employing the ADAR receiver and air-deployed sources. Surface ship programs such as BGMSS and AN/SQQ-89I were also supported by CST. The Battle Group Multistatic Sonar (BGMSS) was designed to provide Battle Group defense by serving as an active adjunct to AN/SQR-18 and -19 operations. The AN/SQQ-89I was to provide improved (one to two convergence zones) performance over that of the existing AN/SQQ-89.

Six technical issues were identified that were of direct concern to all of these programs. CST experiments were designed to address each of the various issues in turn. The key unknown for active systems, moving down to the lower frequencies of interest to CST, was reverberation. Major thrusts were initiated in the program to develop techniques for measuring and characterizing surface, bottom, and volume reverberation. Target strength effects as observed by actual systems, in a waveguide of interest, constituted a second category of CST measurements. The third was the collection of "signal processing issues": evaluation of the wide variety of waveforms, signal processing algorithms, and information processing techniques applicable to LFAA systems. Fourth, propagation effects [transmission loss (TL) and channel impulse response] and forward scattering (loss) required characterization to assess their effects on developing systems. Fifth, source-optimization efforts pursued analyses to determine the optimal use of vertical line array (VLA) sources, taking into account beamwidth, steering, and sidelobe control. Finally, activities in performance analysis and modeling were conducted in an effort to tie all the diverse pieces together to assess the ability of the LFAA community to model the achievable performance of developing systems in environments of interest.

In Phase I of CST, test and analysis products were reported principally on a test-by-test basis. In addition, final results of Phase I were reported in a special issue of the *Journal of Underwater Acoustics* (Vol. 42, No. 2) published in April 1992. As discussed below, in later phases of the program, this important archival final sea test documentation was augmented by a variety of specialized white papers and reports to provide more timely and better-focused products.

CST Phase II History

When CST moved into its second phase in Fiscal Year 1991, it was with the recognition that the scope of the program needed to change in three fundamental ways. First, as the sophistication of LFAA systems development increased, new scientific and technical issues were identified. Second, since the inception of the CST Program, LFAA technologies had matured to the point that increasing the scope of the program to include Acoustic Warfare technologies made sense. Third, with the end of the Cold War, the urgency associated with use of LFAA systems in Third-World arenas or limited-intensity conflicts increased. CST responded to these new needs by expanding the scope of the program's operations to include littoral environments and the unique set of difficulties they posed.

The approach followed by CST in this second phase was a natural evolution of that followed in Phase I. Issues to be addressed were chosen on the basis of their relationship to systems utilization, their importance to underlying science and technology considerations, or their environment-specific nature. CST continued as a highly test-oriented program, with efforts focused as before on an at-sea testbed. To increase the timeliness of program products, however, greater emphasis was placed on providing direct test-and-evaluation support to other systems-development programs.

Figure 4 Sample Products Identified for Transition to the Systems-Development Community

PMS 425 & NAVSEA 92
- Propagation Modeling
- Acoustic Communications
- Advanced Tactical Waveforms
- Battle Group Operations
- Bistatics Threat Evaluation (~1 kHz)
- Shallow-Water Operations

SEA 91W
- System Test Support

PMO 411 & ASTO
- Select a Fusion (C^4I) Engine
- Tactical Bistatics for Current Systems
- Tactical Decision Aids (TDAs)
- LBVDS Waveform Support

PMA 264
- Planar Receiver-Development Support
- Advanced Sources & Waveforms

PMA 299
- Tactical Bistatics

PMW 182
- Mobile Systems
  - R/V *Cory Chouest* Support
  - Multistatics Support
- Fixed Receivers
  - Environmental Support
  - Tactical Frequency Operations (Active & Passive)

DARPA
- Coordinate with Shallow-Water Test Program
- Data Support to Automation

N87
- Bistatic Processor Support
- Test Opportunities
- Communications and Identification Friend or Foe (IFF) Issues

N96
- EVA and Model-Development Support

CNMOC
- EVA and Model-Development Support
- Databases and Survey Techniques

The inclusion of Acoustic Warfare in Phase II of the CST Program was a natural step in the evolution of LFAA systems. When Phase I of the CST Program began, the focus was necessarily on those technologies critical to developing or defining the performance limits of the conceptual detection systems of the day. By the conclusion of Phase I, however, the performance potential of such systems (in deep-water environments) was no longer in question. Many of the remaining questions revolved around the tactics and Command, Control, Communications, and Information (C^3I) needed to operate these systems efficiently and effectively. Acoustic Warfare is the catchphrase for the set of capabilities required to meet that need.

Acoustic Warfare activities in CST explored data-fusion techniques, contact-management tools, operator aids, communications and connectivity requirements, and tactics and doctrine development at the single-platform, Antisubmarine Warfare Commander (ASWC), and Theater Commander levels, all aimed at the effective use of the new set of low-frequency active acoustic tools.

The range of systems being supported by CST increased dramatically from the beginning of the CST Program to the beginning of Phase II. The Phase II CST Program Plan was developed in consultation with these system-development programs, not only identifying their technology requirements but also dovetailing the CST execution schedule with key milestones requiring input regarding these system-development efforts.

The increase in the scope of CST to include operations in littoral areas implied a dramatic increase in the number of candidate theaters, which in turn widened the range of acoustic environments considered by the program. As Phase II progressed, the planned sequence of tests evolved in response to the changing threat climate.

Beginning with CST-5 in 1991, the CST Program was responding to a changing threat environment by beginning to explore the performance of LFAA systems in such locations as the Mediterranean Sea. From that time on, each of the Phase II tests had as its focus a location with unique issues associated with the operation of active acoustic systems, principally in littoral environments. Further, the tests were not always conducted as stand-alone CST exercises, but were frequently conducted in concert with testing by other programs and their developing systems. In particular, the Magellan exercises, by intent, provided a venue for participation by multiple developing systems to resolve technical issues, demonstrate system potential, and address the range of issues associated with system operations and interoperability.

By its final stages, CST was structured as a broad-based program that ran the gamut from conducting analyses in discrete technology areas that underlie applications, through providing direct support to system developers, to addressing the final synthesis problems associated with the Acoustic Warfare applications of multiple systems. In its final two years, the CST Program took conscious steps to focus its activities on transition of program products to the "user community."

Data analyses and final CST products were focused in working groups organized along technology lines. The Environmental Acoustics (EVA) Working Group addressed topics such as surface, bottom, and volume scattering; propagation loss; and ambient noise, especially as they relate to system operations in shallow water. The Signal and Information Processing (S&IP) Working Group addressed waveform design, source operations, spatial and temporal signal processing, and information processing and displays. The Undersea Warfare (USW) Working Group focused on issues that cut across multiple platforms, e.g., tactics, communications and connectivity, contact management and data fusion, and Acoustic Warfare doctrine. The Undersea Warfare Assessment Council (USWAC) comprised a panel of technology users from across the range of system-development and program offices in the air, surface, submarine, and surveillance communities. This group acted as a buffer between the users and the CST working groups, defining requirements to the working groups and bringing focus to the presentation of CST products.

The products generated by the CST working groups were documented in a second special issue of the *Journal of Underwater Acoustics* (Vol. 46, No. 1) published in January 1996, and in a series of focused reports and white papers. As can be seen in the Bibliography, each of these latter documents focuses on CST results relative to a specific technology issue.

Summary

Through the course of its ten-year history, CST has investigated the full range of LFAA technologies, working in environmental acoustics, signal and information processing, and Undersea Warfare.

CST environmental acoustics activities ranged from fundamental explorations of the physics of volume- and boundary-scattering mechanisms, to the utility assessment and enhancement of system performance-prediction tools, with stops along the way to explore LFAA predictive abilities for propagation and distant reverberation.

Signal and information processing includes all the system parameters that are directly under a designer's control. CST has contributed significantly to the understanding of improved waveforms, classification techniques, normalization and optimization for local conditions, improved spatial processors, ping-to-ping processors, and evaluation of alternative system concepts, to name but a few of the topics to be reviewed here.

As Phase II of CST entered the arena of Undersea Warfare, CST supported both individual system-level development and multi-platform LFAA Acoustic Warfare concepts and requirements.

As an experimentally based program, CST sponsored or participated in more than 13 field trials involving the participation of more than 1,000 scientists, engineers, and technicians. The capability to conduct such an extensive experimental program is a key accomplishment and asset of the CST Program. To understand the results achieved by the program requires an understanding of this at-sea capability and methodology. Hence, it is appropriate that we begin this report with a review of the at-sea assets and measurement capabilities developed by the CST Program.

Assets and Measurement Techniques

As a groundbreaking program with an intense experimental focus, CST had to develop a wide range of assets and measurement techniques to accomplish program goals. The success of the CST Program in meeting its wide array of objectives can be largely attributed to the extensive at-sea testing process that was an integral part of the program. Each CST investigation posed unique requirements, many of which forced the development of new technologies.

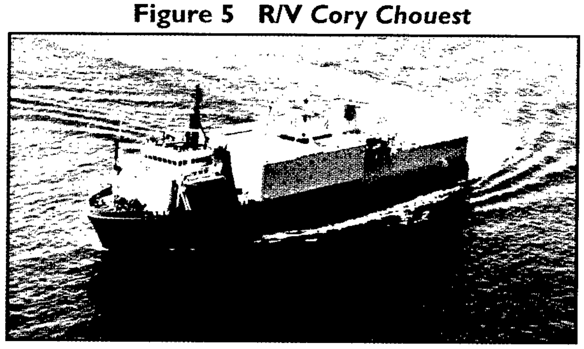
CST testing revolved around the research vessel (R/V) *Cory Chouest*. Development of this platform as an LFAA research testbed set the standard for the possibilities that LFAA technology represents. CST research efforts were supported by a variety of aircraft-, surface ship-, and submarine-based bistatic or multistatic receivers. Participation by such platforms in CST culminated in Magellan I and II, tests that by design explored the Acoustic Warfare interaction and coordination of multiple platforms. Still the suite of measurement capabilities was not complete.

CST measurement goals could not have been met without the aid of a suite of supporting ships, to provide simulated targets (i.e., echo-repeater services) or to act as environmental support platforms. Accomplishment of any of the CST goals required highly specialized measurement tools. Particularly in environmental acoustics, numerous measurement tools were developed and deployed. Further, a major thrust early in the project was development of the high-power, low-frequency sources that were a critical enabling technology for the program.

R/V *Cory Chouest*

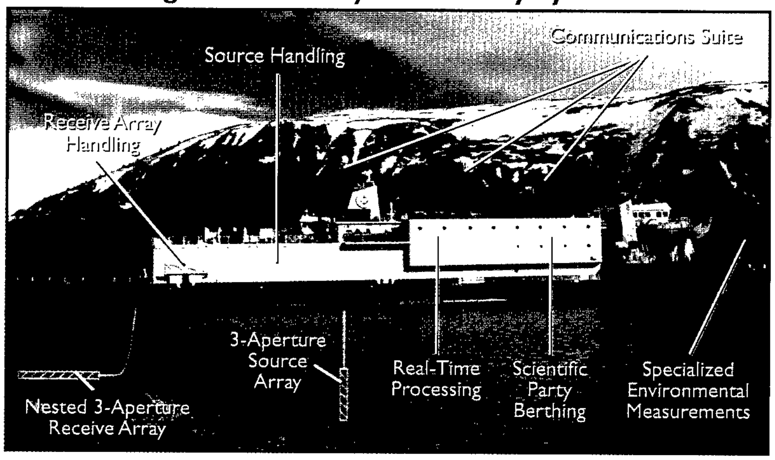
The goal of deploying an at-sea testbed for LFAA research led to the design and development of the now-well-known research vessel, R/V *Cory Chouest* (Figure 5). Owned by Edison Chouest Offshore, this R/V was originally outfitted and operated under lease to PMW 180-5 through a contract with The Johns Hopkins University Applied Physics Laboratory (JHU/APL). R/V *Cory Chouest* underwent reconfiguration for LFAA research in 1987 and, after Coast Guard inspection, was reflagged as a U.S. flag vessel in 1988.

Figure 5 R/V *Cory Chouest*



The R/V *Cory Chouest* was equipped with vertical line array (VLA) sources to span the 50-to-1000-Hz frequency range of interest to the program, a multi-frequency (nested) horizontal line array (HLA) receiver, both real-time and off-line (quick-look) analysis and processing suites, extensive navigation and communication capabilities, and an evolving variety of supporting environmental measurement capabilities (Figure 6). This platform, working in concert with numerous other surface, air, and submarine assets, was the centerpiece of the CST field tests.

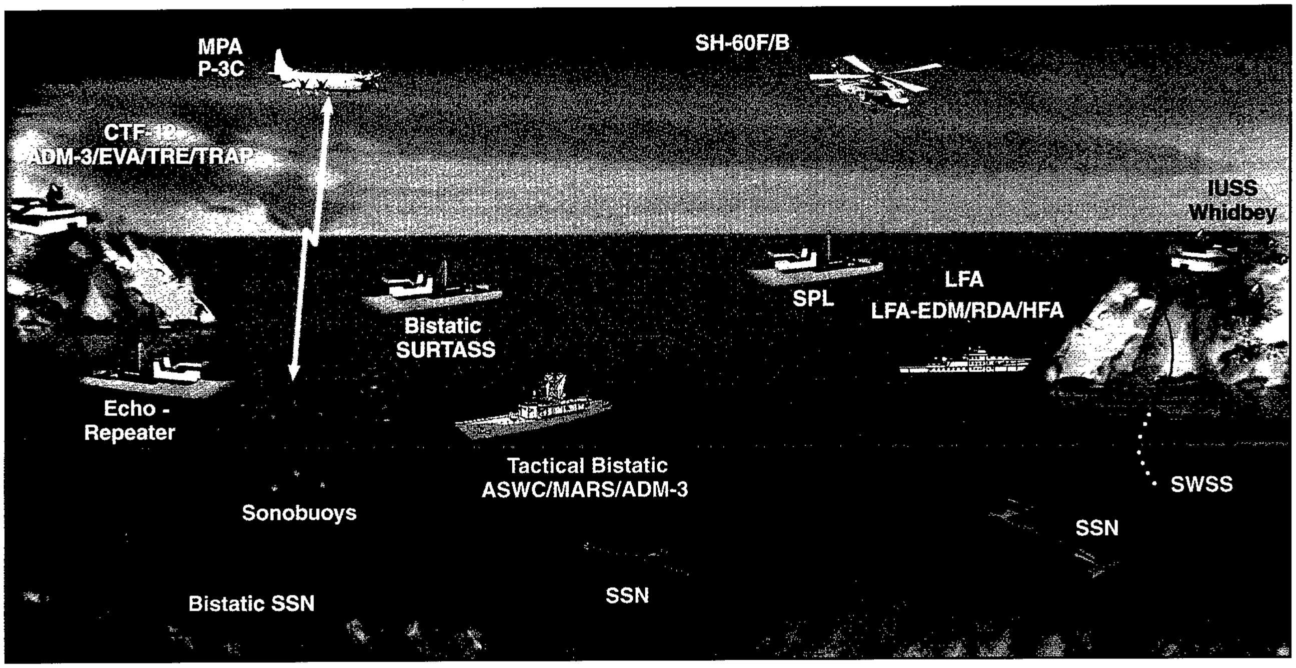
Figure 6 R/V *Cory Chouest*: Key Systems



Quick turnaround of analysis results was a goal of the CST Program from the outset. Recognizing that timeliness of program products was as important as the products themselves, the program used a variety of mechanisms throughout its history to speed the handoff of results to the user community. This approach began with the development and installation on board the R/V *Cory Chouest* of both real-time and quick-look analysis capabilities.

The Real-Time Processor (RTP) was designed to give analysts real-time detection, data quality-control, and data-screening capabilities. Exposing theories and highly controlled test protocols to

Figure 7 Magellan II Test Scenario



near-real-time operational requirements resulted in immediate feedback to the CST Program scientists and engineers regarding the validity and practicality of the theories and protocols. To provide stand-alone capability, an Off-Line Processor (OLP) was developed to provide a standardized set of tools for use in continued at-sea quick-look analyses. The same (Sun workstation-based) software was also distributed for use in post-test laboratory-based analyses. The RTP and OLP capabilities were used to speed the process of data analysis and reporting.

It quickly became apparent that scientific data flow among widely separated platforms would be necessary during the tests, and it later proved true that a similar requirement would exist for actual operational use of LFAA systems. This need was particularly evident for environmental acoustics support, for which management of sound-speed fields covering upwards of 100,000 nmi^2 and evaluation of wide-area bottom reverberation and bathymetry were required. A more detailed discussion of CST's role in developing these capabilities follows.

Bistatic/Multistatic Receivers

In addition to monostatic operations with the R/V *Cory Chouest*, operations using bistatic receivers were a ubiquitous feature of virtually all CST exercises. Because these tests were conducted in oceans throughout the world, it was generally necessary to use Fleet assets as integral components of the tests. The abilities to schedule these assets in coordination with other Fleet requirements; to marshal their efforts toward joint objectives; to install significant scientific, prototype, and LFAA systems; and to train ships' crews in systems operation and utility were hard-won and valuable CST skills.

In CST-1, bistatic concepts were explored, employing air-deployed, AN/SQR-19 (towed array), SURTASS, and fixed receivers. By CST-4, CST had also provided a testbed for evaluation of a submarine bistatic receiver.

Testing associated with the evaluation of individual bistatic system concepts was the chief focus of CST field exercises prior to the onset of the Magellan sequence of exercises. Magellan I and II in many respects represented the culmination of the system-development support aspects of CST; these tests brought the whole concept of Acoustic Warfare to the forefront. Not only were individual monostatic and bistatic receiver concepts explored; these tests also explored and codified the control, communications, connectivity, and coordination issues associated with combined LFAA operations. To support these efforts, CST test activities evolved in the Magellan sequence to include development of tactics; crew training; Command, Control, Communications, Computing, and Information (C^{4}I); and data fusion (Figure 7). As LFAA systems make their way into the Fleet, it is the methods established during these tests that serve as the basis for the introduction of these systems in all Fleet areas, from training to implementation of operational concepts.

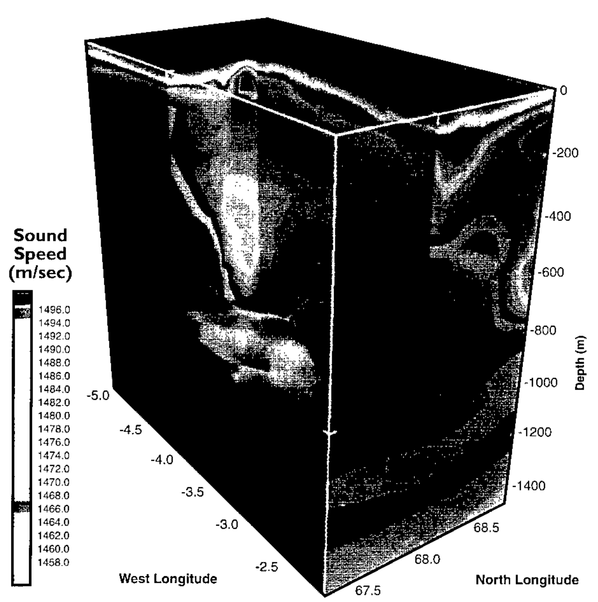
Support Platforms and Assets

Quantification of technology conclusions in support of LFAA systems development often required measurements beyond the capability of the LFAA systems. To this end, CST often augmented its tests with the assets needed to provide the required ancillary measurements. Three significant CST contributions to LFAA testing include the use of an echo-repeater, the environmental characterization required for test sites, and the frequent provision of dedicated environmental measurement platforms.

A key component of almost every CST trial was the use of an echo-repeater. This system served three functions: 1) providing calibrated echoes without the uncertainties associated with actual target strength characteristics, 2) providing more extensive test time than would be practicable using scarce and expensive submarine services, and 3) augmenting the simulated echoes in a variety of ways to enhance the achieved measurements. This echo augmentation included controlled "distortions" of echoes, production of echoes at multiple effective target strengths, time-delay of echoes to exclude reverberation, and transmission of controlled broadband channel-characterization signals.

Throughout the CST Program, major emphasis was placed on providing quality environmental measurements to support interpretation and analysis of acoustic results. The System for At-Sea Environmental Analysis (SASEA) was developed specifically to allow real-time integration and analysis of oceanographic data in support of each CST experiment. This system allowed for the acquisition and integration of measurements from a network of environmental subsystems installed on ships, aircraft, and land-based research stations, providing researchers with near-real-time reports on topics such as weather, satellite imagery, oceanographic assessments, and environmental acoustics as well as generating integrated databases on surface conditions, water column structure, and the three-dimensional sound-speed field (Figure 8).

Figure 8 Three-Dimensional Contour Showing Sound-Speed Field Variations with Depth



Note: Sound-speed contour surfaces < 1464 m/sec have been blanked out, and a cutaway has been made to the eddy core to enhance the view of its structure.

Raw data in support of these interpretive analyses came from a variety of sources. Typically, during CST trials, it was necessary to dedicate air and ship resources to conducting environmental measurements. P-3 aircraft served as the platforms for wide-area oceanographic surveys, frequently supported by a dedicated environmental research ship that either performed higher-resolution surveys or provided support to a variety of dedicated measurement systems.

As CST progressed, it was realized that increasingly sophisticated meteorological measurements would also be required. This led to the development of the Air-Sea Dynamics System (ASDS), first used in CST-4. ASDS, installed on the R/V *Cory Chouest*, provided the full range of meteorological and sea surface measurements needed to perform near-real-time evaluation of the air-sea boundary zone in support of acoustic surface scattering experiments.

As required, CST also defined the necessary communications requirements and protocols to make data available in a timely manner to a diverse set of users over a large operational area.

Specialized Measurements

To meet CST's stated objectives in advancing understanding of environmental acoustics with respect to LFAA systems, several highly specialized environmental acoustic measurement techniques were employed, many developed specifically by CST staff. The principal measurement types were sea surface backscatter, surface reflection loss, bottom backscatter, bottom reflection loss, volume scatter, and transmission loss.

Sea surface backscatter measurements in the CST Program were made using one of two principal types of source transmissions: either short-pulse coherent waveforms or impulsive signals using Signals, Underwater Sound (SUS) explosives. Measurements of sea surface scattering were complemented by techniques developed to characterize the spatial, spectral, and temporal variabilities of surface backscatter, using special-purpose waveforms and near-field beamforming techniques.

Similarly, two techniques were used to measure surface reflection loss. One employed the source- receiver assets on the R/V *Cory Chouest* to transmit and receive short pulses via a surface-reflected path. The second technique, used in the Forward Ocean Surface Scatter (FOSS) experiment during CST-7, measured the forward scattered/reflected field in the top few meters of the water column. Both SUS and short-pulse continuous wave (CW) transmissions from the R/V *Cory Chouest* source array were used, and reception was at a near-surface receive array with hydrophones at 2-m and 5-m depths.

Table 1 Air-Sea Boundary Zone Measurements in CST-7 Phase 2

Feature	Instrumentation Used
Subsurface Bubbles	• SeaScan Bubble Sonar • Bubble Resonator Array
Breaking Waves	• Whitecap Video • FLEX Void-Fraction Drifter
Surface Wavefield	• Datawell WAVEC Buoy • Shipboard Wave Radar • Endeco 1156 Wave Buoy
Wind Speed/Direction and Meteorology	• MINIMET Buoy • Shipboard Air-Sea Dynamics System (ASDS)
Wind Stress	• Fast Sample Anemometer
Water Column Structure	• Expendable Bathythermograph (XBT) • Expendable Conductivity, Temperature, Depth (XCTD) • Airborne XBT (AXBT)

Surface scattering and surface loss measurements were complemented, especially in CST-7 Phase 2, by a variety of measurements to characterize the air-sea boundary zone (Table 1).

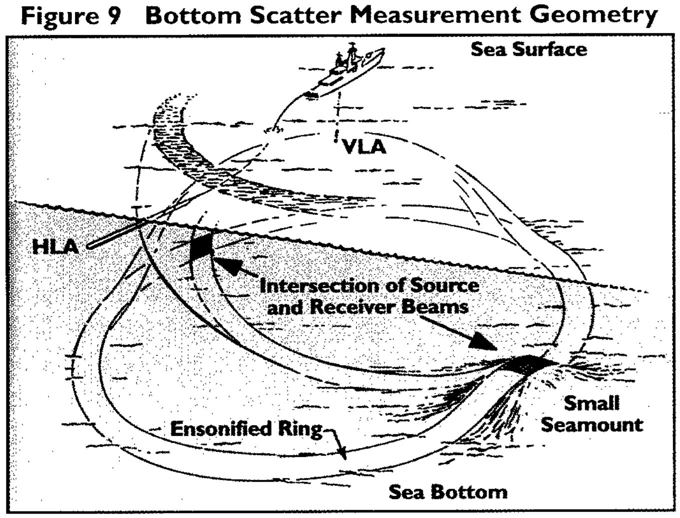
As CST Program emphasis shifted from deep water to the littorals, emphasis on bottom interactions steadily increased. Three approaches were developed for the estimation of bottom backscatter. The first two (Figure 9), employing coherent waveforms and SUS, were analogs of similar techniques employed for estimation of surface scatter. The third approach, model-based extraction of scattering strength, found particular utility in shallow water. In this method, modeled multipath is used in concert with an inversion process to back out the scattering strengths implied by a measured reverberation field.

Bottom loss measurements in CST were made employing separate source and receive platforms, with one platform moving out in range from the other. Sources used were both SUS and modulated waveforms; and a variety of towed HLAs, bottom-moored HLAs and VLAs, surface-tethered VLAs, and sonobuoys were employed as receivers. Measurements were made not only of loss, but also of frequency, angle, and timespread.

To measure volume scattering strength, CST selected measurement techniques that employed broadband acoustic sources coupled with vertically steered receivers. These methods offered both high spectral and high vertical spatial resolution. Measurements were generally conducted to assess both spatial and diurnal variability. The two primary methodologies used were "downward-looking" measurements using a near-surface conical receiver and surface-vented explosives, and "upward-looking" measurements using a deep-deployed VLA receiver and SUS explosive charges. By selectively trading off these two methods, the measurement program was able to trade off frequency-range coverage, water column coverage, and bathymetric limitations.

Throughout CST, transmission loss was routinely measured using a variety of sources (R/V *Cory Chouest* VLA, omnidirectional echo-repeater, and SUS) and receivers (towed arrays, echo-repeater monitor hydrophone, moored and surface-tended arrays, and sonobuoys). The measurements were generally TL surveys, not rigorous scientific measurements of propagation.

Figure 9 Bottom Scatter Measurement Geometry

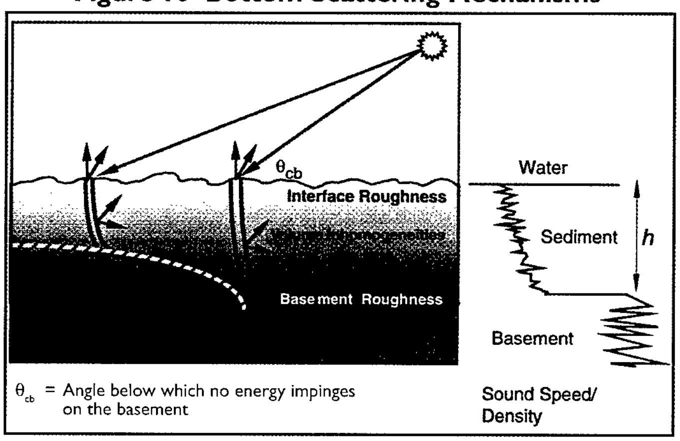


Key Environmental Acoustics Products

Since the inception of CST, major experimental efforts have been directed towards improving the Navy's understanding of environmental acoustics (EVA). CST Phase I (1987-1990) emphasized testing at deep-water sites, while Phase II (1991-1996) focused increasingly on littoral water regions. These measurement efforts addressed important issues in low-frequency (emphasis below 1 kHz) scattering from the ocean bottom, surface, and volume (biologics), and propagation effects. As CST progressed into Phase II, there was increased emphasis on developing an integrated understanding of EVA issues by examining results from all previous CSTs rather than only those from a single test.

As shown in Figure 10, the ocean bottom investigations involved the understanding of the relative contributions due to interaction of acoustic energy with the water-sediment interface, inhomogeneities in the sediment, and the basement.

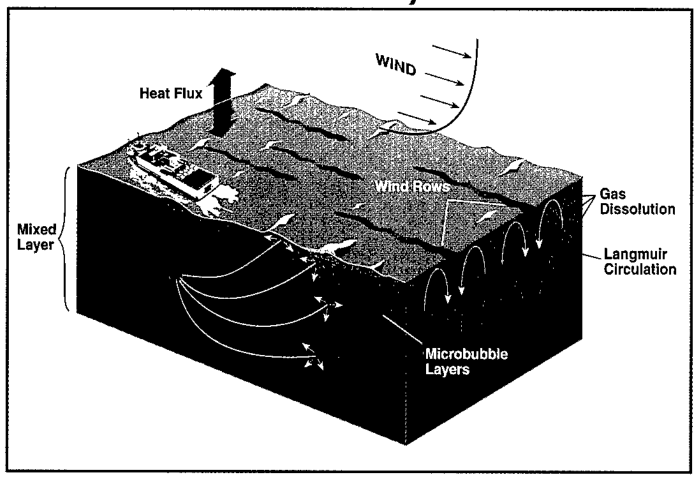
Figure 10 Bottom Scattering Mechanisms



Surface and near-surface investigations also featured competing mechanisms, including the air-water interface, subsurface bubble clouds, and fish schools (Figure 11). When propagation effects were also considered, effective system performance modeling became possible.

CST operations in deep water typically featured either convergence zone or ducted propagation. CST environments in the littoral typically featured one of three types of propagation: ducted, weakly bottom-interactive, or strongly bottom-interactive (modeled at 250 Hz) (Figure 12).

Figure 11 Acoustic Scatter in the Air-Sea Boundary Zone

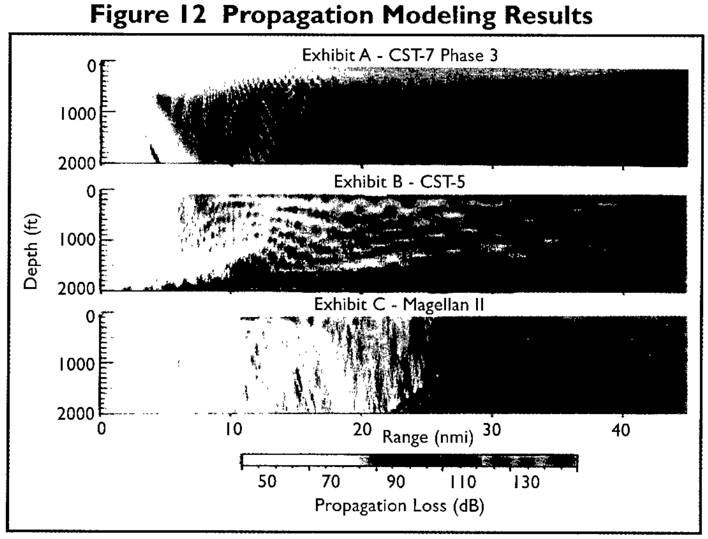


CST EVA Objectives

Objectives of the CST EVA investigations were defined for each of four subtopics. CST efforts sought improvements in the understanding of the following issues:

1. Bottom and Subbottom Scatter Investigations:
    - Bottom scatter measurement techniques
    - Bottom scatter/bottom loss vs. environment
    - Identification of scattering mechanisms
    - Role of subbottom scatterers
    - Long-range and basin-edge reverberation characteristics

Figure 12 Propagation Modeling Results



2. Surface Scatter Investigations:
   - Capability to predict sea surface backscatter characteristics
   - Surface forward loss
   - Surface scatter measurement techniques

3. Volume Scatter Investigations:
   - Capability to predict volume scattering characteristics
   - Volume scatter measurement techniques

4. Propagation Effects Investigations and System Performance Modeling:
   - Capability to measure *in situ* propagation effects for systems adaptation and performance optimization
   - Propagation variability, sensitivities, frequency/angle/time spreading, and refraction effects
   - Capability to predict range-dependent acoustic propagation effects
   - *In situ* system performance-prediction capability
   - Evaluation of source and receiver parameters such as depth, steering angle, beamwidth, and array configuration (e.g., horizontal vs. vertical, bottomed vs. towed).

Initial Status and Milestones

Bottom and Subbottom Scattering

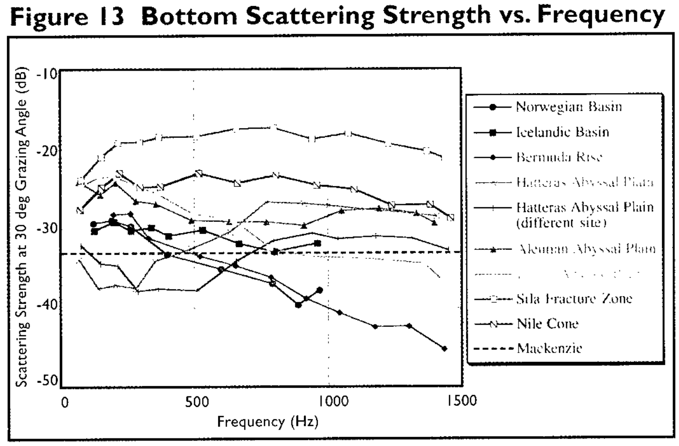
Pre-1987 Status:

- Measured bottom scattering strength data were available, mainly at high frequencies (above 1 kHz); low-frequency estimates were obtained by extrapolation.
- Very little low-grazing-angle (below 25 deg) bottom scattering data was available.
- Mackenzie-Lambert scattering approximation technique had been in Navy-wide usage for decades, with unknown low-grazing-angle errors.
- The importance of subbottom effects in scattering was not well understood.
- Very little geoacoustic modeling had been accomplished to unravel bottom backscattering processes.

Major CST Accomplishments (1987-1996):

- Developed new bottom scattering measurement techniques for low grazing angles (5 to 25 deg).
- Collected substantial number of bottom scatter data sets for a variety of deep and littoral sites at low frequencies (70-1500 Hz).
- Identified complex dependencies of bottom scattering on angle, frequency, and region–reaffirming the inadequacy of the then-current Mackenzie-Lambert standard. An example of the site-dependence of bottom scatter and its exceedence of Mackenzie-Lambert scattering levels is shown in Figure 13.

Figure 13 Bottom Scattering Strength vs. Frequency



- Identified the principal scattering mechanisms in the CST data: sediment volume scattering at low grazing angles and basement scattering at intermediate angles. This understanding provided an initial foundation for extrapolation of measurements in grazing angle, frequency, and environment. Sediment interface scattering did not seem to play a role in CST measurements. The appropriate frequency/grazing angle regions for the different mechanisms and the relevant CST data sets are shown in Figures 14 and 15 for areas with thick and thin sediments, respectively.
- Determined that the survey community needs a survey technique for measuring low-grazing-angle bottom scatter.
- Determined that the current extrapolation technique from mid to low grazing angles can be inadequate, and identified the parameters that define those angular regimes.

Figure 14 Frequency-Grazing Angle Domain: Thick-Sediment Areas

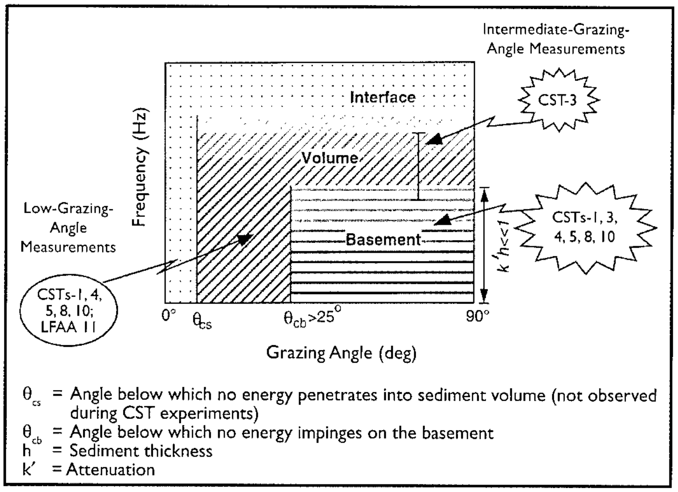
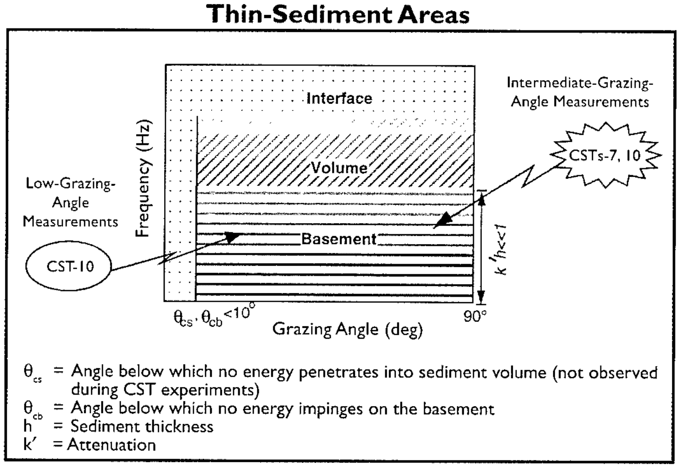


Figure 15 Frequency-Grazing Angle Domain: Thin-Sediment Areas



- Demonstrated that collocated measurements of bottom loss can significantly improve understanding of bottom scatter results.
- Found that coherent and incoherent bottom scatter results appear to be comparable. This finding is important because surveys typically employ incoherent sources.

CST EVA Fleet Products:

- Upgrade of Navy Standard Bottom-Loss Database in Southern California (SOCAL) littoral region submitted to the Oceanographic and Atmospheric Master Library (OAML) in 1996 [POC: C. Holland, Planning Systems Incorporated (PSI)]
- Bottom scattering strength databank delivered to NAVOCEANO in 1996 [POC: R. Gauss, Naval Research Laboratory (NRL)]

Surface Scattering

Pre-1987 Status:

- Chapman-Harris empirical formula had been in Navy-wide usage for decades without full sampling of wind speed, frequency, or grazing angle.
- Physics-based theories of air-water interface scattering (e.g., perturbation theory, composite roughness theory) failed to agree with the few available high-wind measurements.
- Many unexplained surface scattering effects seen in measured LFAA data from Navy experiments such as Artemis, Active Adjunct for Undersea Surveillance (AAUS), and Standard Aura, including a persistent zero-Doppler feature, strong spiky returns, etc.

Major CST Accomplishments (1987-1996):

- Collected large database of high-quality surface scattering data covering wide range of wind speeds (2 to 36 kt) at frequencies from 70 Hz to 1.5 kHz (CST-1 through CST-8).
- Performed high-quality dedicated surface scatter and air-sea boundary interaction experiment (CST-7 Phase 2).
- Demonstrated importance of subsurface bubbles as a dominant scattering mechanism at high wind speeds, and importance of air-sea interface scattering primarily at low wind speeds and low frequencies.
- Developed improved empirical surface scattering algorithms to replace Chapman-Harris algorithm. These new algorithms were based on the observed regimes of different scattering behavior using data from CSTs-1 through -4

Table 2 Confidence Levels for Surface Scattering Strength Algorithm Values

Frequency (Hz)	Grazing Angle (deg)	Chapman-Harris	Ogden-Erskine	Ogden-Nicholas-Erskine
75	10° - 11° 26° - 30°	<0.1% 11%	1.3% >99%	88% >99%
500	10° - 11° 26° - 30°	<0.1% 91%	49% 97%	99% 98%
925	10° - 11° 26° - 30°	1.1% 81%	0.3% 93%	>99% >99%

Figure 16 Wind Speed vs. Frequency Domain

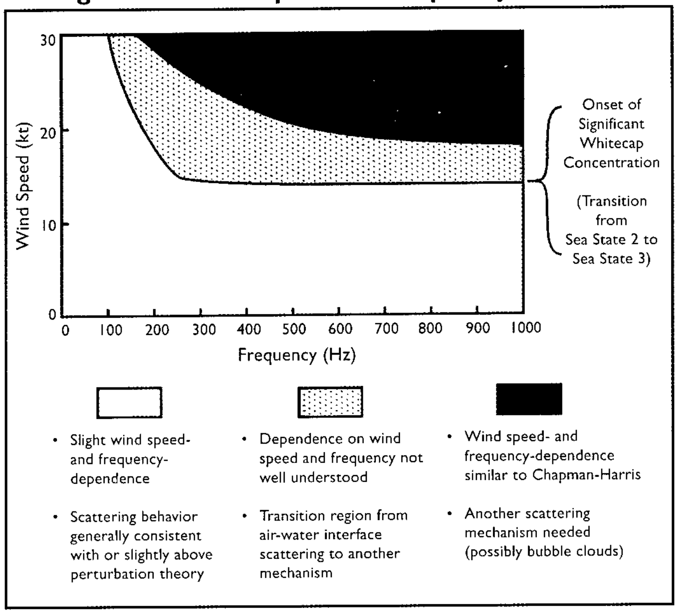
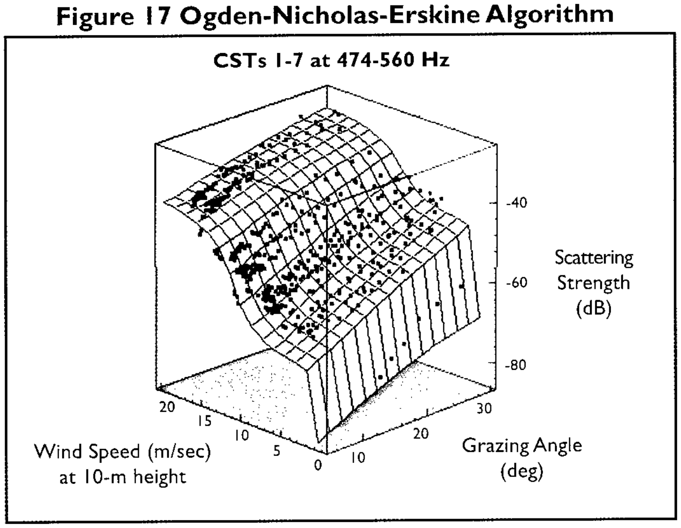


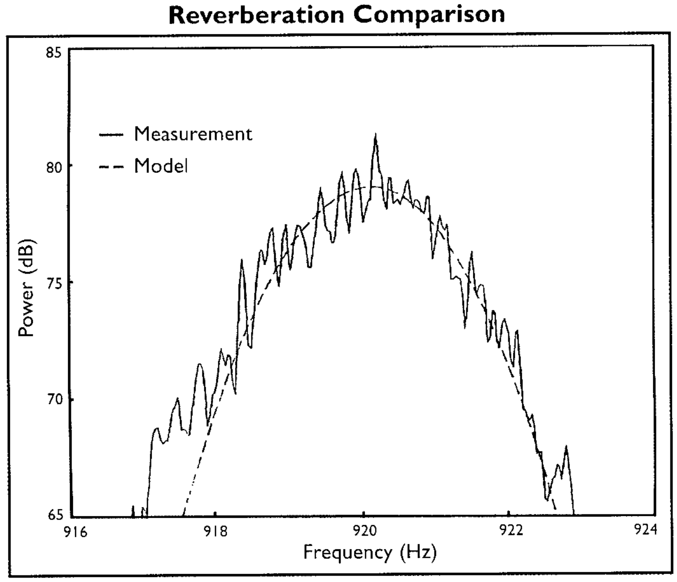
Figure 17 Ogden-Nicholas-Erskine Algorithm



(Figure 16) and were refined to fit data from CSTs-1 through -7 (Figure 17). The improvements in confidence levels for surface scattering strength algorithm values are summarized in Table 2.

- Demonstrated that wind speed (measured at 10-m height) back-averaged about 1 hr is one of the best environmental predictors of surface scattering strength. Differences between surface scattering strengths from CST-4 and those from CST-7 Phase 2 (both conducted in Gulf of Alaska) for equivalent wind speeds indicate that additional factors need further investigation (bubble circulation characteristics, gas solubility, etc.).
- Used imaging measurements to infer that dominant component of surface scattering strength is widespread diffuse bubble clouds (rather than intense localized scatterers in images, which are possibly also due to bubbles, that can be a source of sonar clutter).
- Demonstrated differences between clutter caused by surface scatter and that caused by fish, based on relative lifetimes and frequency characteristics.
- Demonstrated that surface scattering measurements using SUS explosives and those using pulsed waveforms [both CW and Hyperbolic Frequency Modulated(HFM)] give equivalent results.
- Demonstrated convincingly that persistent (but wind-speed-dependent) zero-Doppler spectral component of distant surface reverberation was due to scatterers at depths of 1 to 2 m, convected with mean orbital speed of the surface gravity wave spectrum (strong support for the bubble cloud-scattering hypothesis). The excellent data/model agreement for a surface-reverberation spectrum (pseudo-convergence zone return using a 12-sec CW waveform) is shown in Figure 18.

Figure 18 Measured vs. Modeled Surface Reverberation Comparison



- Determined that Bragg-shifted frequency component of surface reverberation was observed only during low-speed winds (generally below 10 kt) and at low frequencies (generally below 300 Hz), and is well fit by modeling based on air-sea interface scattering.

CST EVA Fleet Products:

- Improved empirical surface scattering algorithms published and submitted for OAML consideration (Ogden-Erskine Algorithm, 1992; Ogden-Nicholas-Erskine Algorithm, 1996) [POC: M. Nicholas (NRL)]
- CST-7 Phase 2 CD-ROM (Meteorology/Surface Wave/Bathythermography (BT)/Subsurface Bubble Concentration) completed. CST wave data from recent tests sent to Fleet Numerical Meteorology and Oceanography Center (FNMOC) in 1996. [POC: J. Hanson (JHU/APL)]

Volume Scattering

Pre-1987 Status:

- An OAML Volume Scattering Strength Database (VSSDB) was in place for high frequencies (2 to 20 kHz). Very few measurements were available in 1- to 2-kHz frequency regime; almost none below 1 kHz.
- The source of volume scatter was known to be relatively large fish.
- Preliminary acoustic scattering models for fish were available.
- Prior to CST-1 in Norwegian Basin, high levels of fish scattering had been predicted for that location.

Major CST Accomplishments (1987-1996):

- Collected substantial new data sets on fish scattering in deep and littoral areas at low frequencies (below 1.5 kHz) where previous data had been sparse. Volume scattering strengths obtained from CST experiment sites are shown in Figures 19 (deep water) and 20 (littoral water).
- Demonstrated that a low-frequency acoustic fish scattering model using fisheries data as input can predict measured volume scattering levels.
- Demonstrated that fish scattering can be comparable to surface or bottom scattering in some geographic areas, even for high wind speeds (good example was CST-1 in Norwegian Basin).

Figure 19 Typical CST Deep-Water Volume Scatter

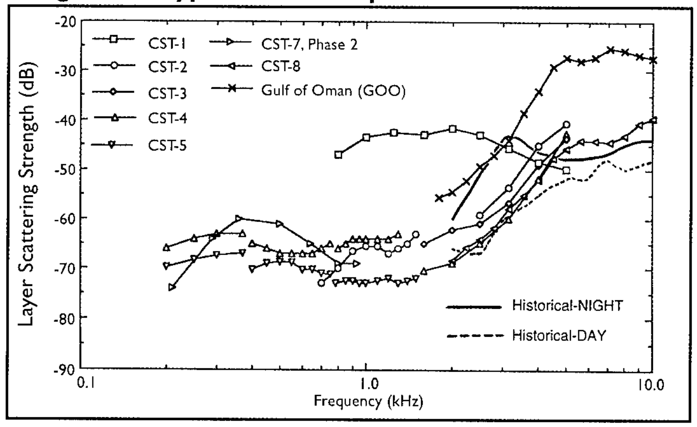
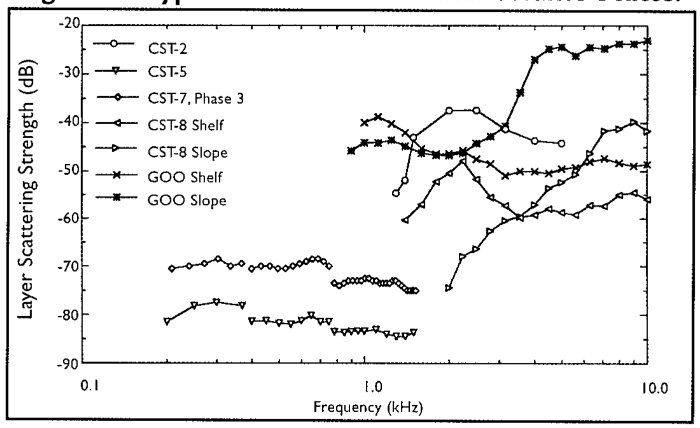


Figure 20 Typical CST Littoral-Water Volume Scatter



- Obtained substantial data sets in deep and littoral areas at tactically relevant frequencies of 2 to 10 kHz.
- Observed resonant scattering from salmon swimbladders in Gulf of Alaska during CST-4 and CST-7 Phase 2, with spectral peak at ~ 400 to 500 Hz and a strong time-of-day (TOD)-dependence (robust scattering during day when fish were at 40-m depth, none at night when fish were near surface).
- Observed low-amplitude volume scattering strengths at low frequencies (below 1.5 kHz) in several littoral regions: Medina Bank, CST-5; eastern Mediterranean, CST-8; Washington coast, CST-7 Phase 3; and Gulf of Oman (GOO). Resonances of fish in littoral waters of the eastern Mediterranean (CST-8) and especially in the Gulf of Oman are likely to result in very high reverberation at high frequencies (5 to 10 kHz).

CST EVA Fleet Products:

- Low-frequency extension to NAVOCEANO's OAML Volume Scattering Strength Database for Pacific north of 30° N and Atlantic and Norwegian Sea east of Greenland and north of SW England, approved 1995 [POCs: R. Love and R. Nero (NRL-Stennis Space Center (NRL-SSC)]

Propagation Effects and Performance Modeling

Pre-1987 Status:

- The ability to model LFAA propagation and system performance was fairly advanced in deep water, more problematic in littoral water.
- Navy Standard Propagation Models included Automated Signal Excess Prediction System (ASEPS) Transmission Loss (ASTRAL) and Parabolic Equation (PE), both range-dependent.
- Existing propagation models had been developed primarily for passive system support (usually intended for single-frequency use); generally did not address time-domain issues such as travel-time structure, waveform-dependence.

Major CST Accomplishments (1987-1996)

- Collected controlled data sets on acoustic propagation at low frequencies (below 1 kHz) in support of all CST experiments in deep and littoral areas. An example of successful propagation-loss modeling is shown in Figure 21.
- Confirmed, through measurements and modeling, that propagation modeling for active system support differs from that needed for passive systems.
- Produced renewed examination of the need for broadband modeling, detailed arrival-time structure, coherent propagation loss estimation, and effects of phase on beam patterns. Most propagation loss models (e.g., Parabolic Equation, Raytrace, Normal Mode) are being upgraded to incorporate these effects.
- Demonstrated the merging and communication of real-time *in situ* sound-speed profiles as well as improved geoacoustic models for effective propagation loss and performance prediction.
- Demonstrated that existing environmental acoustic databases are often inadequate to effectively support modeling in littoral regions (improved bathymetry resolution and a synoptic, current, three-dimensional ocean sound-speed field are needed). This problem is evident in Figure 22, in which the bottom loss

Figure 22 Example of Littoral-Water Propagation-Loss Modeling (CST-8 at 800 Hz)

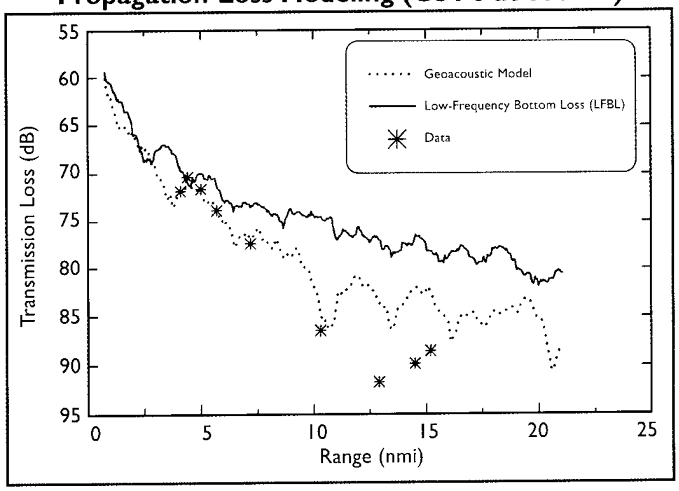


Figure 21 Sample CST Deep-Water Propagation-Loss Modeling (CST-3 at 350 Hz)

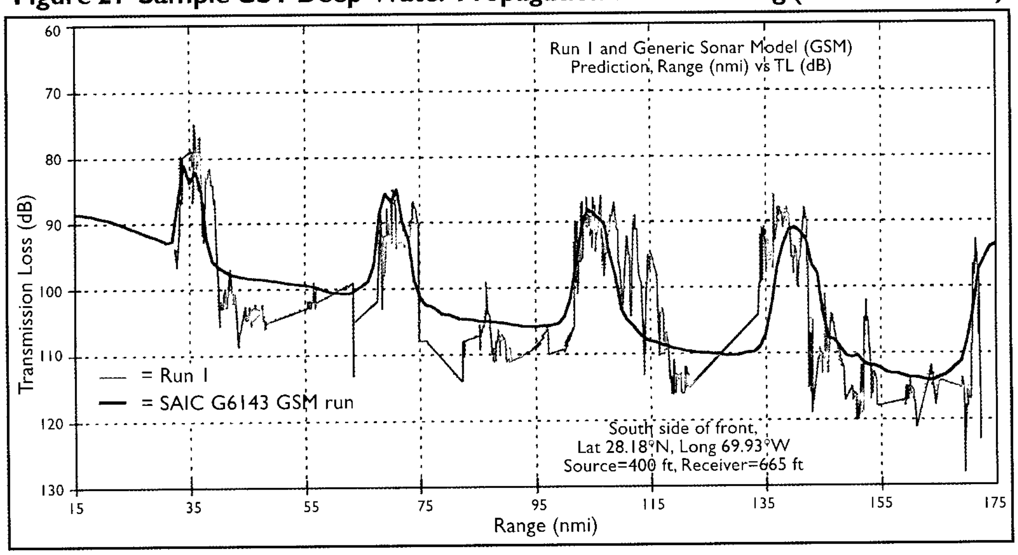
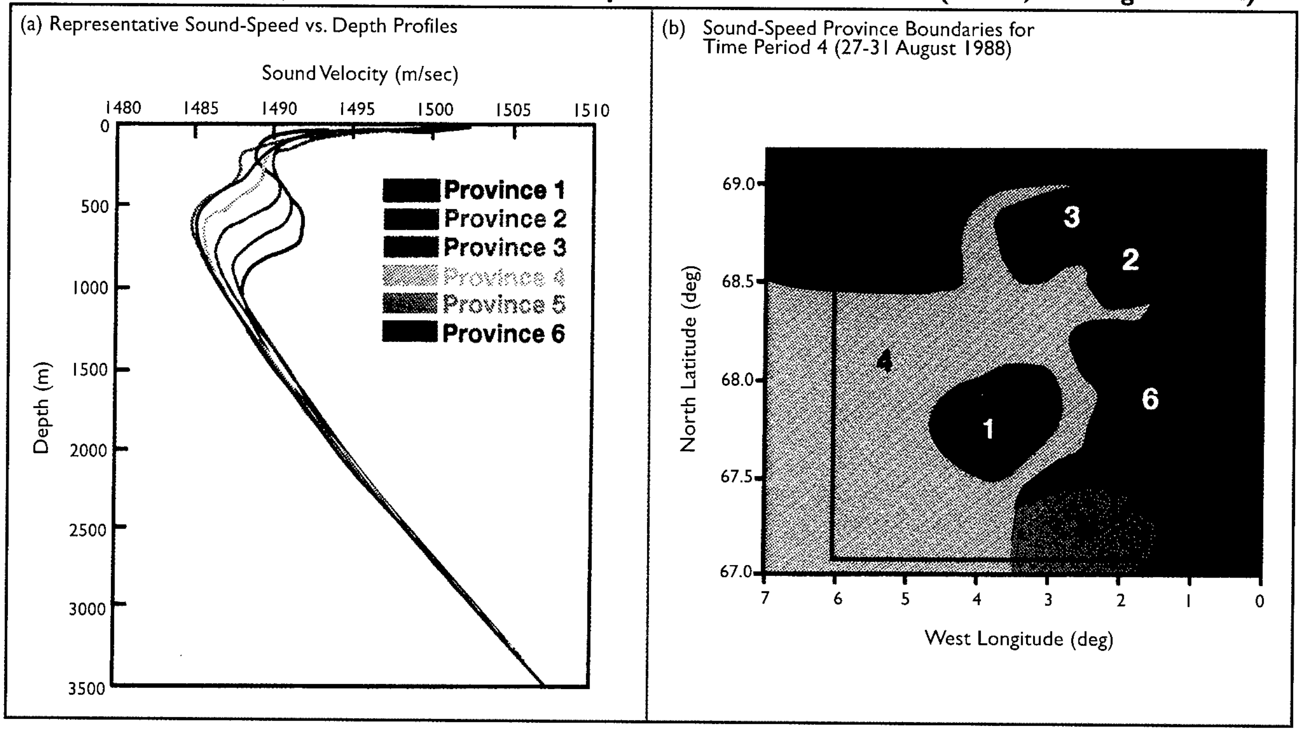


Figure 23 Sound-Speed Profiles and Sound-Speed Province Boundaries (CST-1, Norwegian Basin)



calculation using *in situ* geoacoustic information gives much more accurate values than does the Navy standard database. Figures 23(a) and 23(b) show how a sound-speed field for a particular site (CST-1, Norwegian Basin) was characterized.

- Improved experiment design, analysis, and modeling to better incorporate system details.
- Developed and tested a prototype performance-prediction and analysis capability.
- Implemented a coordinated suite of models and databases in the OLP on board R/V *Cory Chouest* during most of CST and related sea tests. This guided the further development and improvement of performance-prediction technologies, including the determination of which performance-prediction displays (e.g., the plan view of signal excess and the time-varying track

Figure 24 Example of a Plan View of Signal Excess

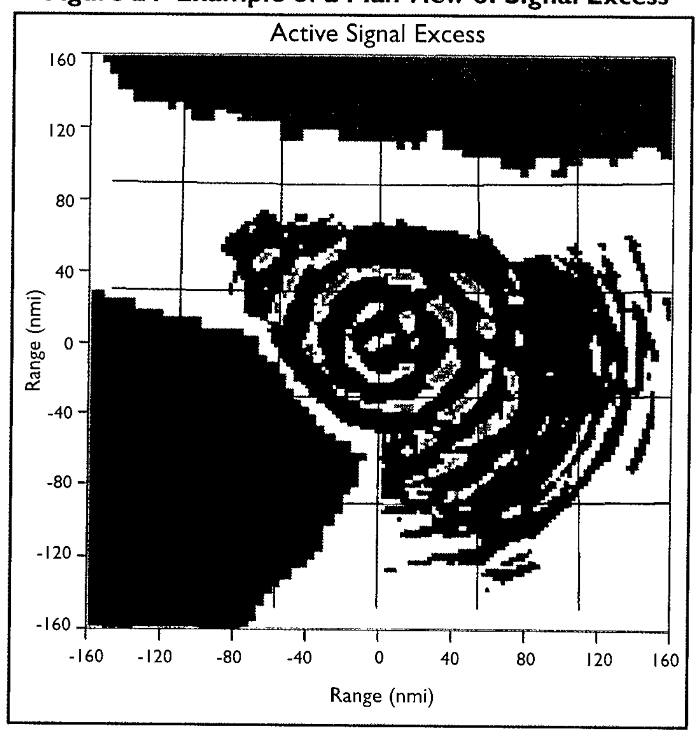
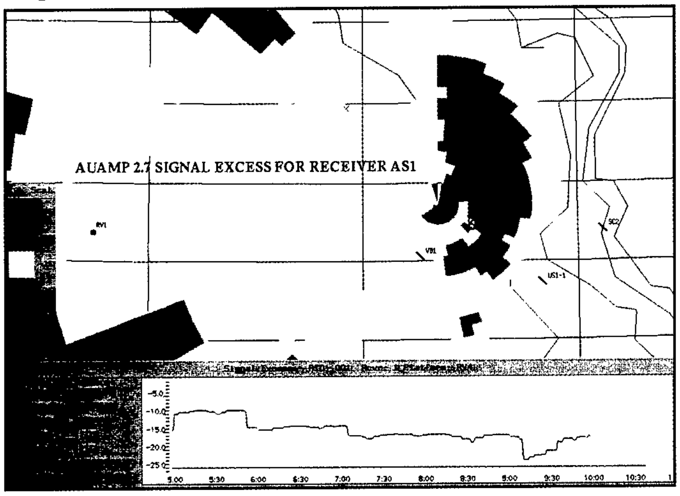


Figure 25 Example of a Time-Varying Track Analysis



analysis shown in Figures 24 and 25, respectively) were ultimately the most helpful.

CST EVA Fleet Products:

- Temperature and salinity data for the Master Oceanographic Observation Data Set (MOODS) Databank and FNMOC. Recent CST environmental data were incorporated into National Oceanographic and Atmospheric Agency (NOAA)/National Ocean Data Center (NODC) World Atlas CD-ROM Data Sets [POC: M. Mandelberg (JHU/APL)].

Key Signal and Information Processing Products

Introduction

The proliferation of modern stealthy submarines continues to force a decline in the performance of passive acoustics surveillance, and current passive capabilities are steadily losing ground to advanced submarine noise-quieting programs. In response, the Navy is promoting LFAA submarine-detection systems to provide an alternative to passive surveillance capability in order to regain tactical advantage in, and control of, Undersea Warfare. Historically, the investigations of active surveillance concepts, which began in the late 1950's, came into full bloom in the 1980's when it became clear that the passive signatures were going to steadily decrease, making passive detection more difficult.

Two active surveillance programs emerged in the 1980's: Standard Aura and the Active Adjunct to Undersea Surveillance (AAUS), marking the beginning of fundamental investigations of basic parameters and capabilities of LFAA detection systems. Originally, the observed quieting of Soviet nuclear-powered submarines on patrol drove LFAA development toward long-range surveillance systems and tactical systems operating in deep water. However, the end of the Cold War focused Navy priorities on regional contingencies and redirected mission requirements of LFAA technology toward littoral environments involving smaller but equally stealthy non-nuclear submarines.

The CST Program was initiated to provide the fundamental technology base to support the growth and development of LFAA capability and applications. A key ingredient of CST support was the development and application of the signal and information processing techniques required to effectively use and transition LFAA technology for all ASW scenarios. Today there are LFAA system processing concepts for virtually every viable platform in ASW scenarios. There are LFAA operational concepts involving monostatic, bistatic, and multistatic systems for surveillance assets, surface combatants, submarines, and aircraft.

CST was chartered to support all technology aspects of the development of deployable LFAA systems, i.e., all aspects of technology implicit within the various terms of the sonar equation. Many CST investigations led to parameter choices that tend to maximize the target's signal-to-noise ratio (SNR) and hence its detectability. Obvious examples of such parameters include frequency, transmitter design, and array design. In addition, because CST management recognized that one of the most important issues associated with LFAA development was the target-classification problem, much of the CST thrust was directed at developing techniques not only for maximizing the SNR but also for distinguishing targets (submarines) from clutter (false contacts).

Clutter signals have enough target-like characteristics to affect (if not overload) the system contact-classification process and performance. As a consequence of its importance, the target-recognition issue received significant attention during the CST activities, and many organizations made significant contributions to its resolution. In particular, significant effort was devoted to exploring waveform properties and signal processing, normalization, and classification approaches.

Although it is not possible to mention all the contributions of CST to the body of knowledge about signal and information processing, many of the most significant contributions are summarized in this section, and many others referenced. Quantitative results dealing with detection performance are necessarily withheld for security reasons. Readers are encouraged to pursue details in the many documents listed in the Bibliography.

Signal and Information Processing

As information flows through a sonar processing system to the sonar operator, it is typically transformed in several stages, including spatial processing, temporal processing, normalization, threshold detection, target classification, and tracking logic (Figure 26). The fundamental goals of these processing stages are to improve the SNR for detection, to provide for discrimination against clutter, and to facilitate correct target classification.

Signal and information processing ultimately is concerned with the process of target detection and classification. This process is enhanced by finding better ways in the detection effort to identify signals (anomalous events in the background) and to classify the detections (determining whether the detection was caused by a submarine or something else); and by finding better methods of localizing, tracking, and cueing.

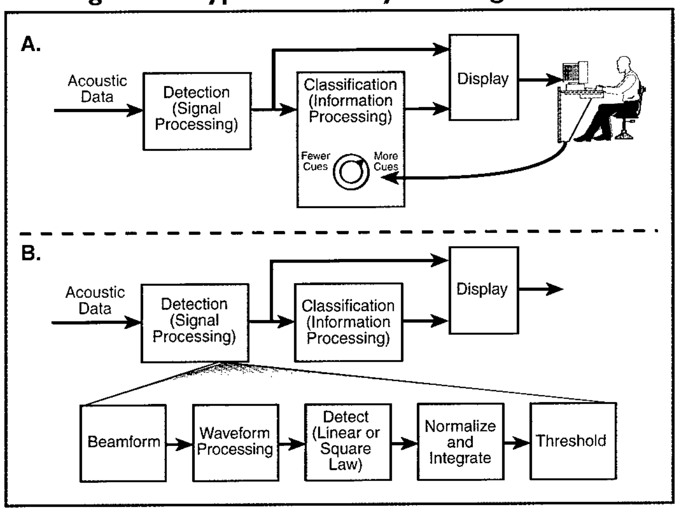


Figure 26 Typical LFAA System Signal Flow

Virtually every aspect of the process shown in Figure 26 was investigated in the CST Program activities. These aspects include beamforming, normalization, waveform design, integration and averaging, clustering, signal attribute extraction, clutter discrimination, and more.

The early CST investigations have been well documented (see Bibliography). These tests dealt with measuring the effects of physical environmental factors on target detectability. The following paragraphs summarize these findings.

Increasing waveform bandwidth reduces both the mean reverberation and target fades and clutter. The principal disadvantages of increased bandwidth are the signal loss associated with the overresolution of target echoes, and the potential for interference with other pings from either the same sonar or other sonars.

Overresolution produces measurable signal losses for operationally significant bandwidths in most environments, particularly in ducted environments. However, even in ducted environments where large spreading losses are expected, increased waveform bandwidth has the advantage of reducing signal fades.

Smoothing of the output of the matched filter, often called overaveraging, is a well-known technique for counteracting range spread of the signal. CST was able to establish with certainty that the range partitioning of echo energy after environmental spreading represents a real limitation of the overaveraging filter that must be accounted for in the filter's design. Too much averaging can actually degrade target detectability.

Range-rate information for sonar contacts can be obtained by using a narrowband waveform to provide spectral separation, using a broadband Doppler-sensitive waveform, or using sequential echoes in a wavetrain to extract range-rate by time-of-arrival estimates after detection. CST investigations validated that all of these Doppler approaches work in agreement with theory.

The most recent CST efforts concentrated on development and documentation of algorithms to improve target detection and classification. Care and emphasis were given to providing the potential user with measures-of-effectiveness (MOEs) and assessments of value added.

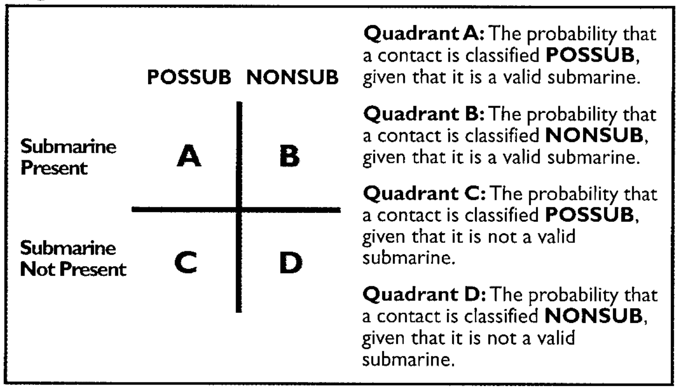
Measures of Effectiveness

Fleet performance requirements are typically specified at the command level or higher, and are translated into requirements for specific platforms. For example, force-level MOEs are intentionally general and deal with the ASW mission, which might be to sink submarines, locate and track submarines, avoid submarines, or protect a carrier or other unit from submarine attack. In general, the specific system/platform performance is quantitatively evaluated, and these measurements are used to assign force-level mission effectiveness values.

Platform performance measurements must address probability of detection as a function of range (and typically of other variables such as cumulative values and lateral range curves), incorporating signal-to-noise characteristics, probability of correct classification, the false alarm rate, and the elapsed time to correct classification. The signal processor, information processor (IP), and display are integral parts in this process.

The IP provides to the operator data that must be examined over all azimuths, ranges, and Dopplers. Although the ultimate goal is full automation, the present state of technology only permits the IP to provide the operator with alerts in prioritizing the search for targets. The effectiveness of the IP is measured in terms of how effectively it provides the operator with target alerts that would otherwise be missed in the press of time and workload. The IP must not only detect the

Figure 27 Confusion Matrix for Contact Classification



presence of an echo in noise; it must also classify the echo as either a submarine target or a non-submarine target. This process is sometimes called a confusion matrix (Figure 27).

False alerts generated by the IP simply increase the operator's workload and degrade the operator's confidence in the automation. A meaningful set of processor metrics includes the target-retention rate, the probability of false alarm, the false alarm rate for the operator workload, and the time to initial alert. These essentials are captured in Figure 28, which represents a format often used to provide a complete report on the effectiveness of the signal and information processor. Shown are performance results categorized by stages of confidence, as a result of the application of various signal processing Doppler estimates and information processing rules. An IP rule of particular interest is *ridge distance measure* (RDM), a metric based upon ranking of contact SNR and Doppler against the contact's nearest neighbors. In general, the probability of detection

Figure 28 Format for Reporting of Processor Performance Results

Category	Doppler ≥ (kt)	IP Rules	SNR ≥ (dB)						
			XXX	XXX	XXX	XXX	XXX	XXX	XXX
Average No. of Clutter Counts/ Ping	0	None	XXX	XXX	XXX	XXX	XXX	XXX	XXX
		w/o RDM	XXX	XXX	XXX	XXX	XXX	XXX	XXX
		All	XXX	XXX	XXX	XXX	XXX	XXX	XXX
	2	None	XXX	XXX	XXX	XXX	XXX	XXX	XXX
		w/o RDM	XXX	XXX	XXX	XXX	XXX	XXX	XXX
		All	XXX	XXX	XXX	XXX	XXX	XXX	XXX
No. of Submarine Contacts Remaining after Application of Rules	0	None	XXX	XXX	XXX	XXX	XXX	XXX	XXX
		w/o RDM	XXX	XXX	XXX	XXX	XXX	XXX	XXX
		All	XXX	XXX	XXX	XXX	XXX	XXX	XXX
	2	None	XXX	XXX	XXX	XXX	XXX	XXX	XXX
		w/o RDM	XXX	XXX	XXX	XXX	XXX	XXX	XXX
		All	XXX	XXX	XXX	XXX	XXX	XXX	XXX
% of Submarine Contacts Cued to Operator	0	None	XXX	XXX	XXX	XXX	XXX	XXX	XXX
		w/o RDM	XXX	XXX	XXX	XXX	XXX	XXX	XXX
		All	XXX	XXX	XXX	XXX	XXX	XXX	XXX
	2	None	XXX	XXX	XXX	XXX	XXX	XXX	XXX
		w/o RDM	XXX	XXX	XXX	XXX	XXX	XXX	XXX
		All	XXX	XXX	XXX	XXX	XXX	XXX	XXX
% of Submarine Contacts Misclassified	0	None	XXX	XXX	XXX	XXX	XXX	XXX	XXX
		w/o RDM	XXX	XXX	XXX	XXX	XXX	XXX	XXX
	2	None	XXX	XXX	XXX	XXX	XXX	XXX	XXX
		w/o RDM	XXX	XXX	XXX	XXX	XXX	XXX	XXX

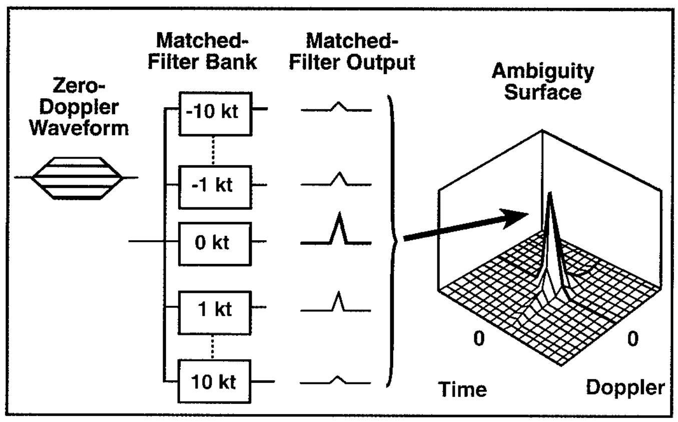
RDM = Ridge distance measure

for the IP must be kept near unity for high-SNR, high-Doppler targets, and also for targets at lower SNR and Doppler that are passed to the system tracker.

Waveform Types and Trade-offs

LFAA systems must operate effectively in diverse environments characterized by anisotropic noise and nonhomogeneous reverberation fields. Although all waveforms perform equally well in noise, appropriately processed waveforms offer fundamental capability to suppress reverberation. The ambiguity function is a powerful descriptor of waveform performance. It describes the matched-filter response for the waveform as a function of time and Doppler mismatch (Figure 29). Using the ambiguity function, waveforms

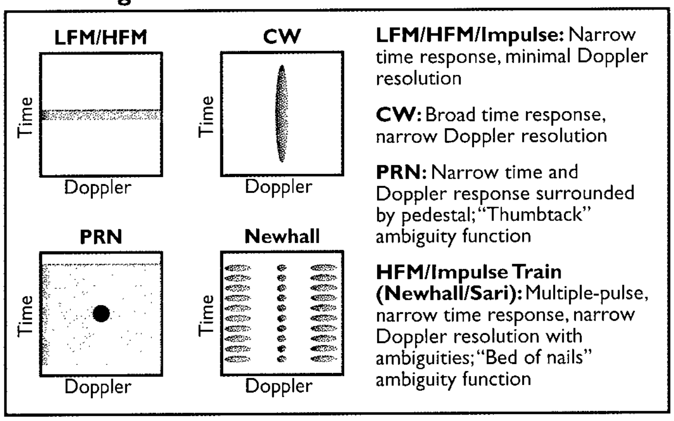
Figure 29 Ambiguity Surface Description of Waveform Performance



can be divided into four common classes (Figure 30): (1) waveforms with ambiguity functions that are narrow in time and extended in Doppler, such as linear and hyperbolic frequency modulated (LFM and HFM) waveforms; (2) waveforms with ambiguity functions that are extended in time and narrow in Doppler, such as continuous wave (CW) waveforms; (3) waveforms for which the ambiguity functions have a peak that is narrow in both time and Doppler, but is surrounded by a pedestal of sidelobes (a "thumbtack") such as the pseudorandom noise (PRN) waveform; and (4) waveforms with a "bed of nails" ambiguity function consisting of a matrix of narrow peaks (a class of waveforms often produced by pulse sequences, e.g., the Newhall waveform).

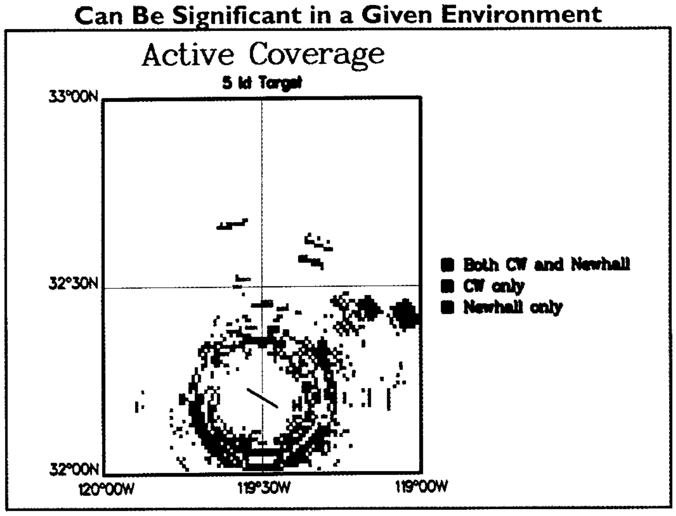
Several factors influence waveform selection for optimal detection and classification performance in a

Figure 30 Classes of LFAA Waveforms



given environment. These factors include target Doppler, reverberation level, own-ship speed, array sidelobes, pulse spreading, and transmission loss (TL). It is impossible to designate one waveform as the best; different waveforms perform better than others in different bearings in the same environment (Figure 31). Taken together in a wavetrain, the LFM/HFM and CW waveforms have good range- and Doppler-resolution properties, and they are an excellent choice for use in deep-water situations exhibiting little reverberation and limited spreading. In the presence of continuous reverberation, both of these waveform types suffer significant detection loss. The HFM and LFM waveforms are unable to reject stationary clutter in preference to moving targets. The only means of reducing reverberation using HFMs is to increase the bandwidth, thus reducing the reverberation scattering area.

Figure 31 Waveform Performance Variation Can Be Significant in a Given Environment



(Figure courtesy of K. J. McCann, JHU/APL)

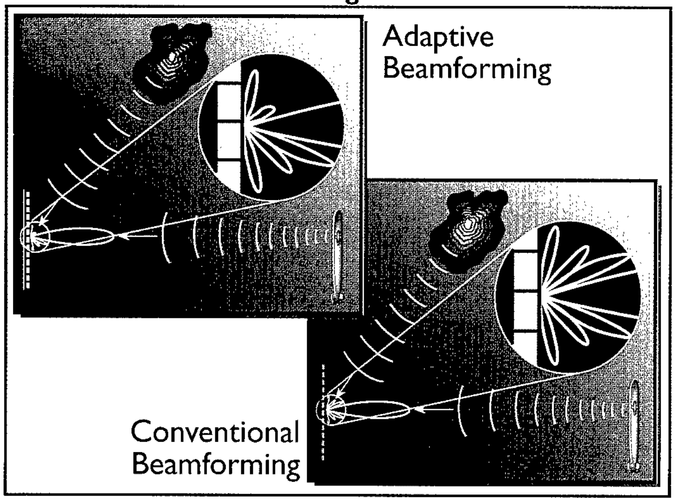
In many shallow-water environments, reverberation is the primary source of interference limiting detection. In highly reverberant backgrounds, the Doppler-sensitive waveforms provide better detection results. The CW waveform is able to reject clutter and reverberation separated from the target Doppler. However, because of the narrowband nature of the CW waveform, the ensonified area is large, and the reverberation levels are large near zero-Doppler. In this circumstance, the target Doppler shift must be sufficiently removed from zero to allow an attractive detection situation. PRN waveforms do not provide rejection for continuous reverberation because of their ambiguity function pedestal, but they do concentrate clutter returns into a narrow zero-Doppler ridge. Finally, Newhall waveforms offer a compromise between using bandwidth to reject continuous reverberation at zero-Doppler and providing Doppler-sensitivity for targets removed from zero-Doppler. Although the detection performance of different waveform classes in the low-to-mid-Doppler region can be marginally poor, the single-ping classification performance of the Newhall waveform can be significantly better.

Adaptive Beamforming

Early sonar techniques in adaptive beamforming (ABF) for passive acoustics applications focused on cancellation of continuous broadband or narrowband interference coming in through array sidelobes. These techniques tended to have long time constants driven by the rate of motion of the interference and by the rate of environmental fluctuations. ABF for active acoustics is challenging because it must cancel discrete echoes, which are characterized by significantly more nonstationarity and more transience. The goal of ABF for active acoustics is the same as that for passive acoustics: rejection of interference received in the array sidelobes as depicted in Figure 32. The beam power is minimized, subject to a constraint of unity response in the steered direction.

The primary measures of ABF effectiveness are measurements of SNR gain (or loss), waveform insensitivity, normalizer threshold crossing rates, and reduction in the clutter Doppler spread. The potential benefits of ABF are numerous, and CST sponsored several approaches to ABF development. Both beam-based and element-based ABF adaptations and new

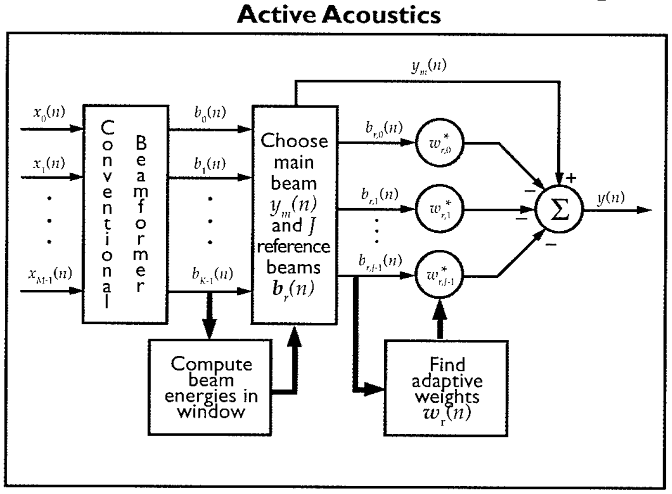
Figure 32 Utility of Adaptive vs. Conventional Beamforming for LFAA



developments were tried in addressing the active acoustics problem.

The beam-based ABF algorithm (Figure 33) is a partially adaptive sidelobe canceler removing sidelobe leakage from conventional beamformed data by using a set of reference beams to estimate the interference. This relatively simple approach provides meaningful performance gains against reverberation and clutter

Figure 33 Beam-Based Adaptive Beamforming for Active Acoustics



when operating in some reverberation-limited environments that exhibit a sufficient degree of spatial anisotropy. Specifically, the algorithm provides gains against reverberation and does not exhibit significant target suppression. The Doppler spread in reverberation and clutter is significantly reduced, thereby permitting enhanced detection opportunities for low-Doppler targets. However, the beam-based ABF algorithm appears to be ineffective against azimuthally uniform reverberation, consistent with the theoretical expectation.

The element-based ABF approach represents the development of a family of algorithms specifically oriented toward adaptation over short intervals. The element-based ABF algorithm employs a novel approach inverting the normal order of applying a matched filter after beamforming. A narrowband beamforming approach is then followed, since the prebeamformed matched-filtered signal now has a low time-bandwidth product. Results show significant gains both in resolution (the ability of the processor to resolve closely spaced objects) and in providing gain while keeping the statistical background noise at a manageable level, as measured by the probability of false alarm versus SNR threshold after Constant False Alarm Rate (CFAR) normalization. Although care must be taken in choosing the algorithm's free parameters, a range of valid parameter values has been identified for the data analyzed to date.

The different approaches for adaptive beamforming have now been investigated for HFM, CW, and impulsive waveforms in relatively harsh environments. The results seem to indicate that as the environment becomes more spatially homogeneous and isotropic, more degrees of freedom are required to produce any significant reverberation cancellation, which favors the element-based algorithms. It is still too early to absolutely recommend a final, robust, and mature algorithm that provides significant interference rejection in all environments without introducing unknown target signal loss. It is encouraging that recent innovations using the beam-based approach allow the ABF to switch automatically to conventional processing in unfavorable conditions. There is impressive information resulting from CST research in ABF, but the algorithms are still under development and require additional testing.

Adaptive Doppler Processing

Adaptive Doppler processing (ADP) is a process closely related to adaptive beamforming. It provides improved SNR by reducing the frequency or Doppler spread, which is an important problem associated with using short-range detection systems in shallow water.

Figure 34 Optimal Formulation of a Matched Filter Process

Reverberation rejection as a function of Doppler and frequency is calculated as:

$$SRR(\alpha_o, \tau_o) = \frac{\int s(t(1+\alpha_o) - \tau_o) \cdot w(t - \tau_o) dt}{Q_{SW}}$$

$$Q_{SW} = \iint x_{SW}(\alpha', \tau') \cdot S(\alpha', \tau' - \tau_o) \, d\alpha' \, d\tau',$$

where s is a signal with spectrum S,
w is the signal replica,
τ_0 is a time delay,
α_0 is a Doppler compression factor,
Q_{SW} is the generalized Q-function, and
$x_{SW}(\alpha, \tau)$ is the cross-ambiguity function between $s(t)$ and $w(t)$.

Conventional Doppler processing relies on long waveforms to produce high spectral resolution, but long waveforms can also produce an extended direct-blast zone in which detection is limited. Therefore, short-range system designers compromise by using relatively short waveforms, thus degrading performance of conventional Doppler processors against the background reverberation spectral spread.

The conventional Doppler processor simply correlates the received signal with a Doppler-shifted replica of the transmitted signal. On the other hand, it is possible to consider the formulation of the optimum receiver to find a correlation kernel that maximizes the signal-to-noise ratio at each Doppler hypothesis (Figure 34), with the clutter covariance matrix taking the place of the cross-sensor covariance matrix. The relative gains for this method are shown in Figure 35, which demonstrates the advantages of this technique at low Doppler values.

The ADP technique offers little advantage over ABF at high Dopplers because the sidelobes of the signal autoambiguity function are already quite low. Also, the ADP processor is ineffective when the ratio of the energy at zero-Doppler to the energy in the Doppler sidebands decreases. This describes the condition in which reverberation becomes effectively spread over a broad Doppler range, which is analogous to the isotropic reverberation condition in adaptive beamforming.

Fixed and Distributed Systems

The Navy has considerable interest in and experience with fixed bottom-mounted sensor systems. Furthermore, sonobuoy fields are distributed systems of nearly fixed receivers that have been in general use for many years. A natural step in LFAA technology transition was investigation of the potential of ensonifying fixed systems and distributed fields; typical receivers were deployed in numerous CST tests.

One of the several advantages of using fixed or nearly fixed receivers is that within certain constraints, reverberation and clutter tend to replicate over several LFAA ping cycles. This makes it possible to discriminate against fixed reverberation with respect to moving targets. CST explored and refined concepts exploiting the spatial and temporal coherence of the environment to create favorable situations for target detection. Both coherent and noncoherent techniques were developed, using full adaptive coherent cancellation and incoherent tracking. Both the coherent and the noncoherent clutter-suppression techniques require some minimal amount of target motion to prevent the target echoes from being canceled along with the clutter. The ability of these techniques to remove clutter and to retain slowly moving targets is a critical determinant of their effectiveness.

Figure 35 Effectiveness of Adaptive Doppler Processing in Reducing Zero-Doppler Ridge

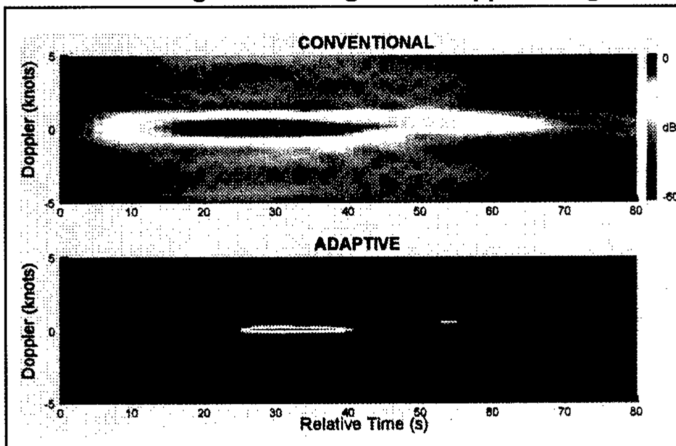
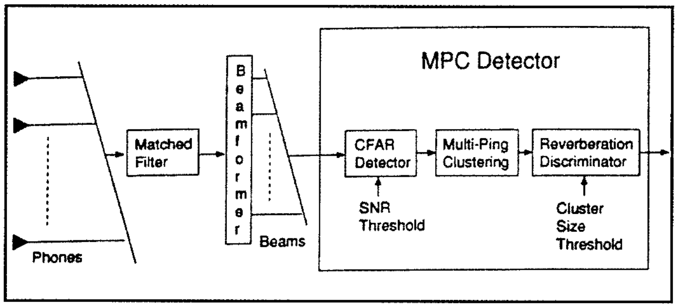


Figure 36 Multi-Ping Clustering to Remove Stationary Clutter

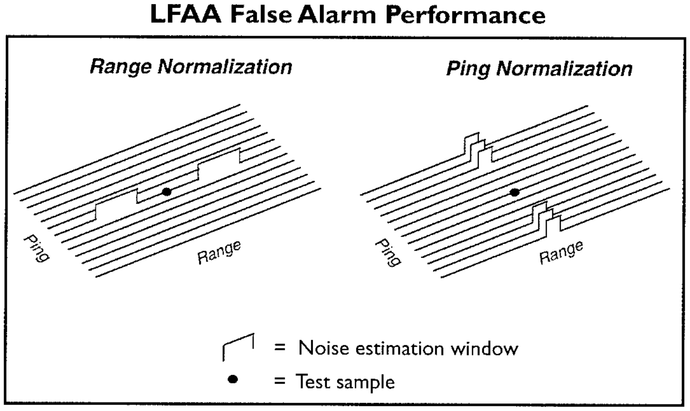


Clustering Techniques

The Multi-Ping Clustering (MPC) technique (Figure 36) is a noncoherent technique that provides gains against repeatable clutter and reverberation. Target-like reverberators are sufficiently consistent to allow clustering of returns across multiple pings in beam/ range space. Fixed reverberator echoes tend to occur at the same time relative to the direct blast if the source and receiver are stationary. Slowly moving sources and receivers can be compensated for their motion. Clusters of echoes from fixed reverberators developed over many contiguous pings tend to grow much larger than those clusters representing target echoes. Great cluster size is a good indicator of the need for the removal of echoes from fixed reverberators. In contrast, echoes from moving targets generate smaller clusters and are easily recognized as they form tracks.

The Ping-Wise Normalizer (Figure 37) is a process that alleviates the non-Gaussian and nonstationary nature of echoes prevalent in active sonar systems. Reverberation threshold crossings from conventional

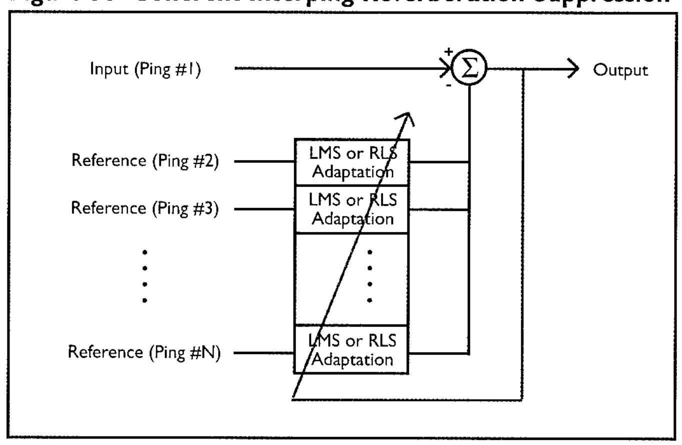
Figure 37 Ping-Wise Normalization to Improve LFAA False Alarm Performance



range-only normalization occur much more frequently than predicted by Gaussian assumptions, and tend to cause increased false alarm problems. The Ping-Wise Normalizer uses the basic idea that with a slowly moving (or stationary) source and receiver, the reverberation samples in consecutive pings come from the same physical reverberators. Normalization across pings is not subject to common estimation limitations caused by nonstationarity in the range direction, and the threshold crossing statistics become much more Gaussian.

Coherent Interping Reverberation Suppression (CIRS) exploits the reverberation coherence across pings (Figure 38). This method is based on the assumption that the characteristics of the reverberation at the

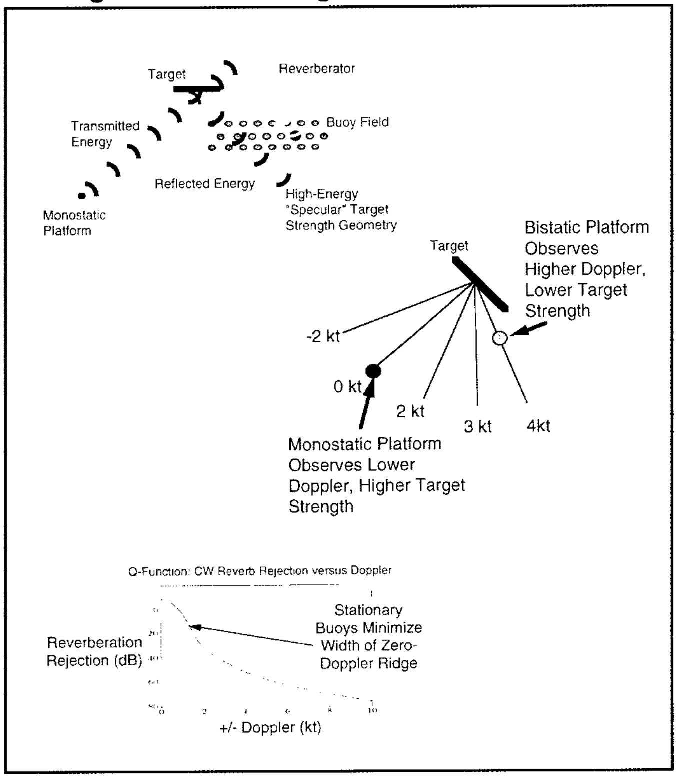
Figure 38 Coherent Interping Reverberation Suppression



LMS = Least mean square
RLS = Recursive least squares

receiver are similar from one ping to the next. The common reverberation component can be recognized and removed, thereby improving the probability of detection. The reference signal for the subtraction is typically obtained from prior or subsequently received pings. The filtered reference signal is subtracted from the input to obtain an output signal with minimum power. The subtraction is implemented with an adaptive noise canceler to optimize the reduction of the reverberation. Interping coherence is a function of Doppler bandwidth and environmental location. It is easily measured, and is an effective indicator of reverberation suppression. For the CIRS technique to be effective, targets must be preserved, and their echoes must decorrelate from ping to ping (a process that requires some target motion).

Figure 39 Processing for Distributed Fields



Air Bistatics Processing

Distributed fields provide 1) spatial diversity advantages resulting from the multiple combinations of transmission loss from the target to the receivers, 2) the opportunity for the receivers to observe different target aspects, and 3) the opportunity for the receivers to receive different target Dopplers (Figure 39). These advantages provide unique detection opportunities for bistatic receivers in the field.

A number of lessons were learned from conducting several air bistatics operations during the CST, LFA, and LLFA test series. Littoral water environments were emphasized, and the tests provided ample proof-of-concept that air-deployed bistatic sensors can detect and track in shallow water. These tests also demonstrated that clutter-reduction techniques are critical to successful processing and tracking. Issues related to using sonobuoys as bistatic receivers concern the buoy-deployment configuration, buoy beam steering, buoy-deployment depth, and buoy lifetime. Proper distributed field design must emphasize exploiting spatial diversity, taking into account direct-blast masking and waveform design. Many of the lessons learned in CST about waveform design for monostatic systems also apply to air bistatic receivers, and they underscore the importance of using reverberation-suppression waveforms. Finally, the CST lessons learned included development of methods using ellipses intersecting in the same location in geospace. Using multiple-buoy detections over time and space provides an effective approach to target detection and clutter control.

Of particular note when using Directional Fixing and Ranging (DIFAR) buoys for deployment of bistatic receivers: these buoys provide not only the omnidirectional receiver but also the north-south (N/S) and east-west (E/W) dipole receivers. Gain against reverberation and clutter can be obtained by processing these buoys to steer the dipole beams in desirable directions and by forming the cardioid beam, also steered for maximum rejection (Figure 40).

Figure 40 DIFAR Processing for LFAA

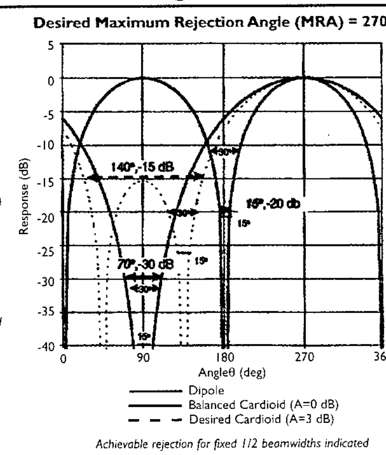
Formulation

Dipole
Single degree of freedom (θ)
n/s $\times$ $\cos\theta$+e/w $\times$ $\sin\theta$

Cardioid
Two degrees of freedom (θ,A)
omni + A (n/s $\times$ $\cos\theta$+e/w $\times$ $\sin\theta$)

Performance Measures

	Dipole	Cardioid *Balanced*	Cardioid *Desired*
Beamwidth (deg)	2×90	130	120
2nd Array Gain (dB)	3	4	5
3rd Array Gain (dB)	4.7	5	6
Null Level (dB)	-40	-40	-15
Useful Null (dB)	-20	-30	-15
Null Width (deg)	-15	70	140



The dipoles and the cardioid can be steered to avoid loud or distributed discrete interference. The cardioid beam pattern provides slightly more gain than does the dipole pattern. The dipole rejects reverberation at right angles to the receiver beam axis, and the cardioid rejects reverberation in the opposite direction to the main axis. These two techniques of forming beams and steering the beams are well-developed, and the theoretical gains associated with their use compare favorably to the measured gains for both relatively isotropic reverberation and rejection of discrete reverberation.

Undersea Warfare Products and Systems Implications

Introduction

A significant objective of the CST Program was to develop a theoretical and empirical understanding of each of the governing factors in the LFAA problem, with the emphasis on environmental acoustic (EVA) and signal processing issues. The program succeeded both at this task and in another area, one not as clearly defined at the outset of the program: LFAA applications in Undersea Warfare (USW). That area emerged in Phase II of the CST Program.

One of the principal accomplishments of the CST Program was the definition of a totally new class of sonar systems in the LFAA band (Table 3), with strong synergistic ties to "passive acoustic systems," both surveillance and tactical. Originally conceived as the frequency zone for very-long-range deep-water sonar systems, LFAA systems also proved, in a variety of operational tests, to be key contenders for use in littoral waters as well. The defining characteristics of LFAA systems (Figure 41) include simple delimiters such as bandwidth, source level, and array gain; but also extend to intersystem communications, and to data flow, display, and storage. LFAA system products also include the net gains achievable with joint operations among diverse systems.

Finally, the LFAA sensor operator was given the ability to "tune" these new systems. This ability to adapt waveform- and signal-processing approaches for specific tactical and environmental situations is perhaps both the strongest feature of LFAA systems and the greatest contribution of the overall CST Program. The development tools necessary to achieving this ability are based in the generic system approach to system design and performance, as well as in the Team USW approach to system employment. The very significant results summarized in this report came from the application of these tools in an operational testing environment, and from a real-time synthesis of research, engineering, and design evaluations conducted in operationally important locations around the world.

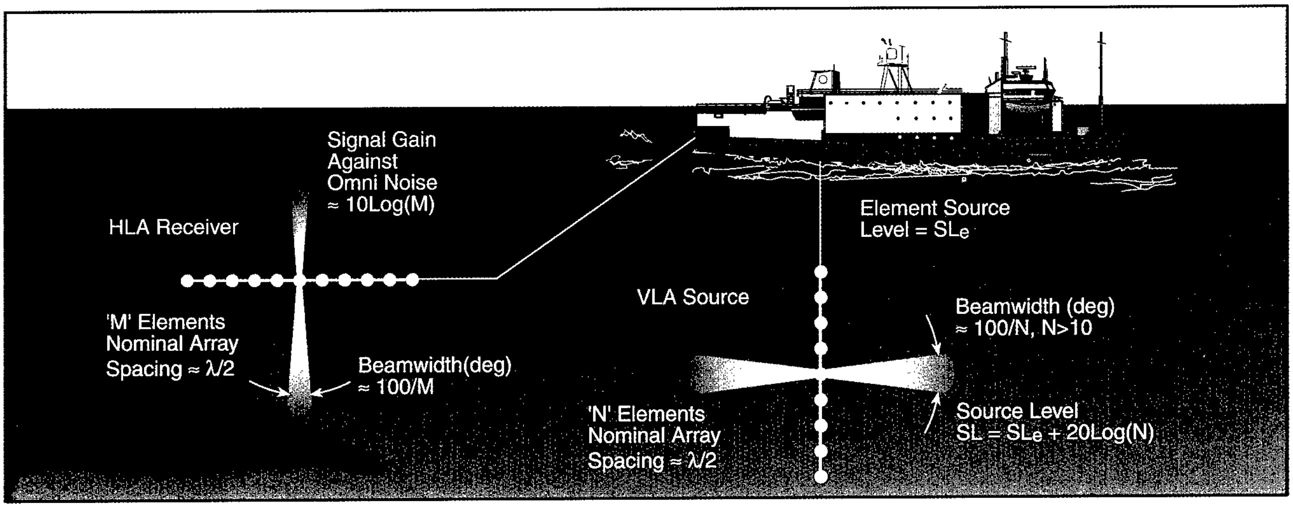
LFAA Generic Sonar System Concept

The term "generic system" is used here as an emulation of a system concept using only a few simple physical parameters and sonar equation descriptors. The salient characteristics of a VLA of sources and an HLA receiver can be well defined by describing 1) the number and spacing of the array elements and 2) the acoustic properties of the individual elements. These few parameters describe such characteristics as array directivity, beamwidth, and beam source level. In fact, few propagation or performance models can accept

Table 3 Key Differences Between LFAA Systems and Earlier Acoustic Systems

System Feature	System Era	
	Pre-LFAA	LFAA
Frequency Band	f > 2 kHz	f < 1 kHz
Detection Path (Deep)	Direct path or single refracted path [bottom bounce (BB) or convergence zone (CZ)]	Direct path and multi-refractive
Detection Path (Littoral)	Direct path only	Direct Path and multi-refractive
Processing Approach	Hardwired	EVA and site-adaptive
Waveform Types	Preconfigured, small selection	EVA and site-adaptive
Environmental Acoustics (EVA) Requirements	Local Sound Speed Profile (SSP)	Multiple SSPs, range-dependent, detailed bottom topography, generally EVA-intensive
Command, Control, Communications, Computing, and Information (C^4I)	Single-platform contact and prosecution, some surface-to-air cueing	Multi-platform interactive, multi-sensor contact and prosecution. Data fusion and Tactical Decision Aids (TDAs) required.
Cue-To-Kill	Own-platform sensors and weapons	Cued platform relocation and weapon delivery required; position error- and time-late-sensitive.

Figure 41 LFAA Sonar Concept



any more information than this. From this modest information set, one can infer information about characteristic system size and handling properties.

The generic system approach is logically extended to receivers as well as sources. By allowing these source/receiver sets to use either impulsive or modulated (including Doppler-sensitive and Doppler-insensitive) waveforms, to possess either high or low apertures, and to move or remain stationary, one can define a very significant portion of the overall capability of these instruments in any given operating area (Table 4).

Table 4 Comparison of Source and Receiver Types Jointly Tested During CST

Source Type	Receiver Type		
	Fixed (VLA & HLA)	**Towed (High-Aperture HLA)**	**Air-Deployed (Low-Aperture VLA)**
Fixed (VLA)	• Minimal testing with high-aperture sources and existing high-aperture fixed receivers • Low operational interest	• Minimal testing with high-aperture sources and existing high-aperture towed receivers • Low operational interest	• Minimal testing with high-aperture sources and existing low-aperture air-deployed receivers • Low operational interest
Towed (VLA)	• Minimal testing • Augmentation of fixed-barrier operations • Low operational interest	• Significant testing with both high-aperture LFAA sources and existing tactical and surveillance receivers in deep and littoral environments • Very high U.S. and foreign operational interest throughout LFAA band	• Significant testing with high-aperture sources and low-aperture receivers • Medium operational interest
Air-Deployed (Low-Aperture VLA)	• Minimal testing • Augmentation of fixed-barrier operations • Medium operational interest	• Minimal testing • Augmentation of general multistatic operations • Low operational interest	• Significant non-CST testing • Multiple applications in deep and littoral environments • Very high operational interest

System Frequency Selection

The process of adapting a generic design to specific performance requirements is an iterative spiral in which an initial set of design parameters is chosen and the resultant system capability is compared against performance requirements. Usually use of the initial parameter set will result in failure to achieve some facet of performance, and the design parameters will have to be varied to correct the deficiency (e.g., by adding more elements to a receiver to obtain better array gain, or using multiple apertures for lower- or higher-frequency capability). These parameter changes lead to trade-offs in other areas (e.g., a longer array is heavier, bulkier, and harder to turn around, and it probably tows at slower speeds) until a promising design is achieved. A significant contribution of the CST Program to this generic process for LFAA system design is the basic understanding of the variability of each of the sonar equation terms as a function of frequency (50 to 1000 Hz) and operating environment (Table 5).

Table 5 Key Sonar System Design and Operational Issues

Sonar System Type (Frequency Band)		
LLFA	**LFAA "Surveillance"**	**LFAA "Tactical"**
Source Issues		
• VLA Aperture ⇒ 100 to 400 m • Long-range capability implies high element source levels, complex design, great size and weight, and high cost. • Unlikely to be towable source • Limited bandwidth • Significant band-reuse problems, including: –Variable physics across band (sonar equation, all terms) – Mutual interference	• VLA Aperture ⇒ 50 to 100 m • Long-range capability implies high element source levels. • Capability proven using specially designed platform • Low tow speeds necessary (less than 4 kt) • Moderate bandwidth • Some band-reuse problems	• VLA Aperture ⇒ 15 to 50 m • Mid-range capability demonstrated in CST • LFAA prototypes under development in U.S. and foreign countries have been tested, proofed, and documented; significant number of systems will be operational by 2000. • Tow speeds of 10 to 20 kt may be feasible. • Substantial bandwidth • Minimal band-reuse problems
Receiver Issues		
• HLA Aperture ⇒ 1000 to 4000 m • Array length compatible with that of existing high-gain passive arrays • Potential for significant active/passive synergism • Low tow speeds and array length require ~ 1 hr or more for array to regain stability after large maneuvers. • HLA receiver directivity allows maneuvering to place target in quiet beams. • Good distant propagation implies diverse reverberation products in deep-ocean areas and band-reuse issues.	• HLA Aperture ⇒ 500 to 1000 m • Proven capability, system in Fleet introduction • Significant active/passive synergism demonstrated • Moderate tow speeds and array length require ~ 3/4 hr or more for array to regain stability after large maneuvers. • Receiver directivity allows maneuvering to place target in quiet beams.	• HLA Aperture ⇒ 150 to 500 m • Tactical tow speeds and array length require ~ 10 min or more for array to regain stability after large maneuvers. • Receiver directivity allows maneuvering to place target in quiet beams. • Speed capability is factor of 4 or more greater than that of towed passive systems because of high active SNRs and operation out of flow noise regime.
Noise Level Issues		
• Band dominated by shipping noise • ~ 8 dB above LFAA surveillance band • ~ 10 dB above tactical band • Most potential for interference with passive operations • 10 dB higher at low end of band	• Mixture of shipping noise- and sea state noise-dependency • ~ 8 dB below LLFA band • ~ 2 dB above tactical band • Some potential for interference with passive operations	• Most dominated by sea-state-proportional noise • ~ 10 dB below LLFA band • ~ 2 dB below LFAA surveillance band • Least potential for interference with passive operations
Reverberation Level Issues		
• Reduced TL implies increased basin boundary reverberation. • Mixed physics region, different scattering mechanisms within band • Most difficult problem is low-Doppler target in boundary reverberation. • Insignificant volume and surface reverberation	• Same issues as for LLFA band, with reduced variability across band • Most difficult problem is low-Doppler target in boundary reverberation. • Little potential for volume or surface reverberation	• Greater potential for volume scattering (bubbles and biologics) and surface scattering (sea state-dependent) • Most difficult problem is low-Doppler target in boundary reverberation.
Transmission Loss Issues		
• Transmission mode variability across band, especially in bottom-interacting water • Generally excellent propagation at long ranges • Below cut-off for littoral ducted conditions at low end of band	• Good long-range propagation • Littoral and duct propagation	• Generally good propagation with some fall-off at long ranges and in shallow water at the upper end of the band

Performance Prediction

The ability to predict the performance of a generic LFAA system operated in concert with other sensor systems requires a more extensive approach than that historically used in calculating simple monostatic signal excess, i.e., "Range of the Day." This new approach is necessitated not only by the extensive LFAA detection ranges and the associated requirement for accurate, large-scale environmental acoustic information, but also by issues associated with multiple-sensor integrated operations such as C^4I, mutual interference, and cue-to-kill. One approach to calculating multiple-sensor performance is the Multistatic Sonar Equation.

Figure 42 Broadband Sonar Equations

Figure of Merit

$$FOM_{ij} = SL_i + PG_i + TS_{ij} - (NL_{bm})_j - DT_j$$

Signal-to-Noise Ratio

$$SNR_{ij} = SL_i + PG_i + TS_{ij} - (TL_{st} + TL_{tr})_{ij} - (NL_{bm})_j$$

Signal Excess

$$SE_{ij} = FOM_{ij} - (TL_{st} + TL_{tr})_{ij} = SNR_{ij} - DT_j$$

Target Absolute Value

$$RL_{ij} = SL_i + PG_i + TS_{ij} - (TL_{st} + TL_{tr})_{ij}$$

where $(\ )_{ij}$ => the i^{th} source and the j^{th} receiver and s,t,r => source, target, receiver, respectively

The Broadband Multistatic Sonar Equations

Performance analysis of an arbitrary pairing of an assemblage of these generic sources [characterized by source level (SL) or source energy level (SEL)] and receivers can be accomplished using the multistatic broadband sonar equation set (Figure 42). These equations are powerful tools in understanding and predicting the performance of different configurations of sensors in a given environment. To understand the interplay of these sensors, it is important to realize that only transmission loss (*TL*) and target strength (*TS*) are strongly dependent on both source and receiver locations, and that accurately calculating these quantities will largely dictate bistatic success.

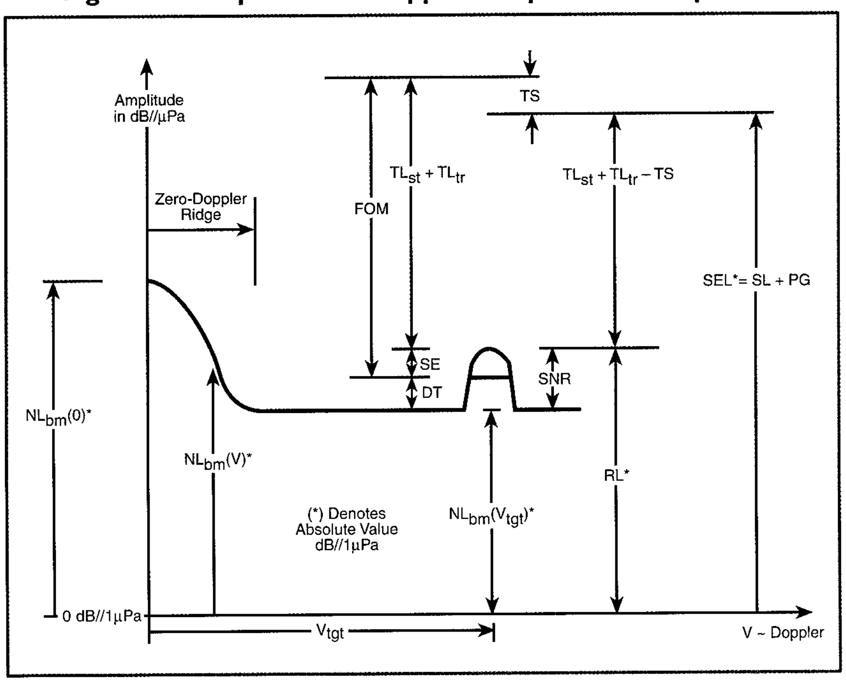
Achieving excess energy on the target and receiving target-reflected energy at a receiver are chiefly positioning requirements involving both path (e.g., convergence zone) identification and transmission loss along the path, but are also waveform- and wavetrain-selection issues. Wavetrain extent implies blanking zone extent; waveform extent allows for processing gain (PG) as well as Doppler- or range-resolution capability. The effects of noise and reverberation are displayed here as a single term, beam noise (NL_{bm}), i.e., the term actually displayed and measured on an operational LFAA system. In an omni-noise (NL) environment,

$$NL_{bm} = NL - AG$$

where AG = array gain.

Achieving signal excess (SE) [i.e., signal above some detection threshold (DT)] at a receiver is largely a function of 1) controlling noise and reverberation through signal processing and 2) receiver positioning and orientation. The relational aspects of the sonar equation can also be displayed graphically. In Figure 43, they have been adapted to a Doppler detection display. Similar representations can be adapted for any waveform type. This figure dramatically depicts the large dynamic range of the *TL* and noise/reverberation (*RL*) terms. The degree of control that the system has over these two terms will determine success or failure at achieving signal excess.

Figure 43 Amplitude vs. Doppler Graphic Sonar Equation



Multistatic Concepts

One of the major advances in USW concepts explored in CST and related test programs is the use of the multistatic concept of sensor deployment: one or more sources can be used to ensonify a search area populated by numerous separated receivers of differing configurations. This approach allows for a significant enhancement in USW performance, due largely to the target's inability to easily identify the scope or location of the passive receiver field. Illustrated in Figure 44 are several key aspects of this approach in a deep-water noise-limited environment. Here a single source operates with three receivers. The properties of these receivers are summarized in Table 6.

Figure 44 Multistatic Concept of Sensor Deployment in Deep-Water Noise-Limited Environment

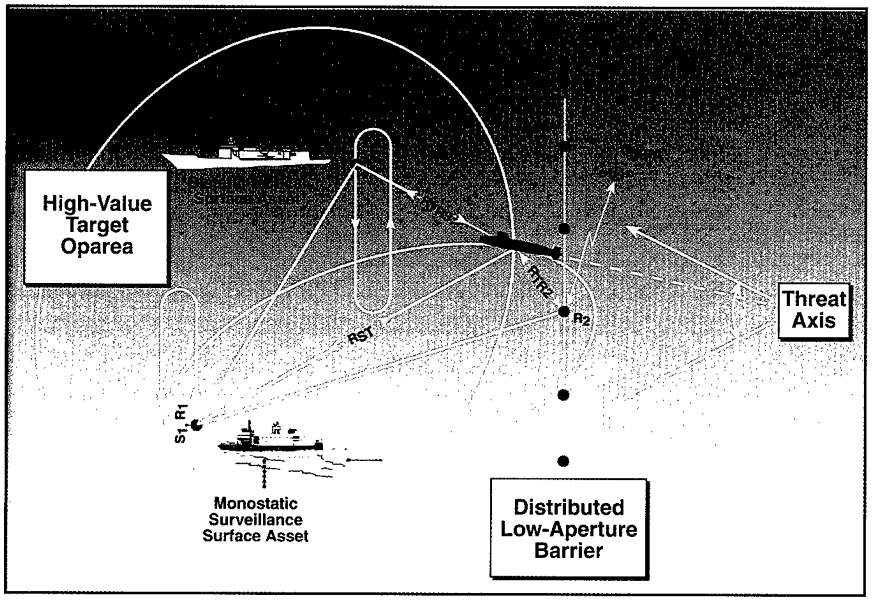


Table 6 Operational Issues and Signal Excess Characteristics at Each Receiver

	Signal Excess Characteristics		
Receiver ID	**R_1**	**R_2**	**R_3**
Deployment Strategy and Issues	• Protection of High-Value Target oparea • Low-speed receiver • High-gain source and receiver • Search path normal to threat axis • Cueing platform only to Marine Patrol Aircraft (MPA) or tactical platform's helicopter	• Immobile receiver • Low-gain receiver of "trip line barrier" • Barrier laid normal to threat axis • MPA monitoring of Receiver R_2 • MPA relocation sensor and weapon capability	• High-speed receiver • Medium-gain receiver • Source/Receiver (S_1/R_3) axis normal to threat axis • Receiver R_3 can cue MPA or own tactical track-and-kill capability (hull-mounted or helicopter-based systems)
Transmission Loss (TL)	• Monostatic • Puts energy in target search area • $2TL_{11}=(TL_{ST}+TL_{TR})_{11}\approx 2[68+10Log(R_{ST})]$	• Bistatic gain over $2TL_{11}$ • $2TL_{12}\approx 2TL_{11}-10Log(R_{ST}/R_{TR2})$	• Bistatic gain over $2TL_{11}$ • $2TL_{13}\approx 2TL_{11}-10Log(R_{ST}/R_{TR3})$
Wavetrain (WT) Type	• Combination of range- and Doppler-sensitivity	• Interleaved short-range waveform range-sensitivity	• Combination of range- and Doppler-sensitivity
Array Gain (AG)	• High aperture (A_1) AG_1	• Small aperture (A_2) $AG_2 = AG_1 - 10Log(A_1/A_2)$	• Tactical aperture(A_3) $AG_3 = AG_1 - 10Log(A_1/A_3)$ • Receiver R_3 should be positioned to minimize noise/reverberation in search beams.
Target Strength (TS)	• Low; bow quarter (Aspect ≈ 045°)	• High; bistatic beam aspect (Aspect ≈090°)	• Low; bow aspect (Aspect≈000°)
Target Doppler	• Medium ≈ $0.7V_{tgt}$ noise-limited detection	• Zero-Doppler; reverberation-limited detection	• High ≈V_{tgt} noise-limited detection
Detection Threshold (DT), False Alarm Rate (FAR), and Contact Classification	• High-gain array provides good potential for initial detection and tracking on all waveforms. Initial detection will reduce DT on others.	• Good potential for initial high-Doppler detection and tracking	• High-TS hit on specular receiver (consistent with Doppler detections on Receivers R_1 and R_3) enhances classification and provides good cueing for further MPA prosecution.
Cue-To-Kill	• Can provide most accurate cueing position to tactical platforms.	• Coordinate cueing of MPA and/or platform's own helicopter from contact on Receiver R_1 or R_3. • T_{LAG} minimum for cueing helicopter from R_3 contact position.	• Direct cueing from R_2 contact, coordinated cueing from surface tactical platform for contacts on R_1 or R_3 • T_{LAG} minimum for cueing from own R_2 contact position.

Team USW Concept

The Team USW approach to planning and strategy (see Table 7) was conceived during the early bistatic testing phases of the CST and LFA/SURTASS Programs as a way to 1) logically deploy sensors having different capabilities and characteristics, 2) quantify the gains achievable with multiple sensors, and 3) highlight the need for an overall scheme of communication, especially inter-system data transfer, that smoothly transitions the phases of the process from the detection phase through kill.

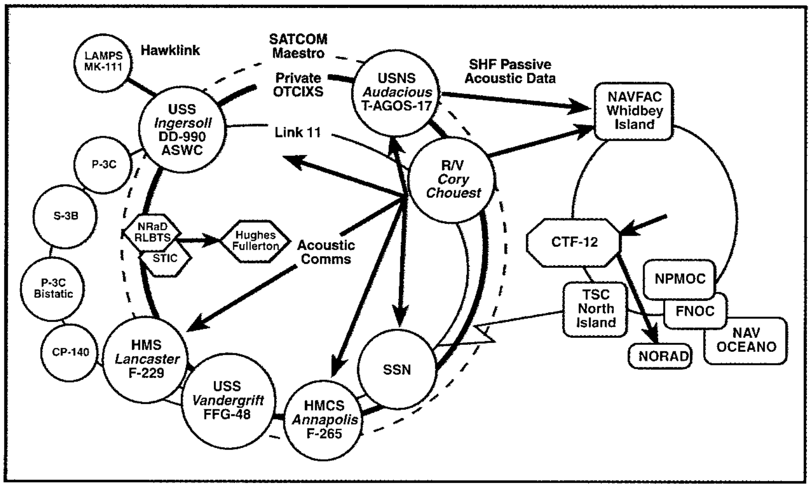
Table 7 Team USW Concept

Key Process Facets	Sequential Process				
	Establishment of Threat Mission(s) and Capabilities	**Initial USW Team Placement for Search/Detection**	**Search and Detection Phase**	**Target Classification**	**Localization and Cue-To-Kill**
Objectives	• Review past mission profile and current intelligence. • Develop operational profile for each anticipated mission. • Assess target strength estimates. • Assess radiated noise and transients.	• Establish area environmental acoustics (EVA) characteristics: transmission loss (TL), reverb, and noise fields. • Accomplish initial placement of sources and receivers based on expected threat profile and EVA characteristics. • Evaluate platform mission assignments and iterate for multiple-threat missions. • Maximize team bandwidth through waveform (WF) design, and source timing and placement.	• Put energy on target • Establish energy/depth envelope of control. • Maximize team bandwidth. • Understand and establish control over area noise and reverberation.	• Establish target track, multiple-sensor pairs if possible. • Obtain confirming passive and non-acoustic signatures. • Ensure rapid transfer of initial contact information to all sensor pairs. • Establish and maintain real-time fusion plot (manual or TDA-based).	• Select track/kill platforms including relocation sensor loadout and weapons. • Establish the relocation sensor range, R_{loc}, and the cueing data transfer time lag, T_{lag}. • Evaluate cueing capability in terms of target speed, V_{tgt}: $R_{loc} > T_{lag} x V_{tgt}$ • Control mutual interference between cueing and relocation sensor systems.
Team Enhancement Methods	• Employ multiple assets to cover all threat-vulnerability issues (e.g., location and signature type).	• Achieve enhanced coverage by using multiple sensors. • Obtain *in situ* feedback from individual sensors on local EVA.	• Use nonacoustic sensors outside of envelope. • Limit target's control of aspect (TS) and motion (Doppler) through use of multiple sensors, WF selection, and stealthy receivers. • Establish optimum sensor pairs with best Se_{ij}. • Accomplish sequential glimpse tracking using various sensor combinations. • Achieve enhanced detection threshold (DT). • Assess potential gain from decreasing bistatic TL.	• Enhance tracking capability with multi-sensor field. • Reduce False Alarm Rate (FAR) due to quick multi-sensor assessment of first contacts, especially joint tracking with matching Doppler. • Implement rapid switch from unalerted DT to alerted status to enhance multi-sensor target detection. • Use multi-sensor fusion to aid track-before-classify capability.	• Enhance cueing from multi-sensor tracking. • Investigate potential for same-platform track and cueing control.
Command, Control, Communications, Computing, and Information (C^4I) Requirements	• Planning authority access to threat intelligence databases	• Early establishment of dedicated team net at the initial planning stages • EVA data connectivity • Continued data integration with threat data updates • Connectivity with nonacoustic sensor/databases	• Dedicated team net (absolute requirement) • Backup net • Both data and voice circuits • Adjunct communications as available	• Team net for data input to fusion and TDA assessment tools (critical requirement) • Real-time feedback to team members regarding contact classification needed	• Switchover from a data-driven fusion process to single-sensor cueing for relocation sensor and weapon placement. (Experience indicates that direct real-time voice comms may be needed to reduce T_{lag} and to ensure reliability of data transfer at this stage.)
Key Ongoing Issues	• Need for threat database in Tactical Decision Aid (TDA) format	• Need for EVA data accession/modeling and multi-sensor signal excess in TDA format	• Need for *in situ* assessment capability in TDA format • Possible limitations of existing voice and data circuits in real-time multi-situation environments	• Need for proven data-fusion tracker • Lack of *in situ* TDA for real-time assessment • Degrading of data fusion due to time-late of secure comms in real-time operations	• Additional real-time training (marrying the multi-sensor team approach to existing Fleet sensor and weapons system usage) that is being conducted using LFAA prototype systems

LFAA C⁴I and Cue-To-Kill

The second phase of the CST Program placed great emphasis on developing the tools necessary to effectively implement the coordination and data-transfer requirements of LFAA Team USW. The Navy's approach to problems of this type falls under the umbrella of Command, Control, Communications, Computing, and Information (C^4I). As shown in Table 7, this aspect of the problem was of critical importance to overall success. A key component of all CST testing was the establishment of real-time secure communications and data links as required among all exercise participants.

Figure 45 Connectivity in Magellan II



A specific example of the connectivity established during the Magellan II test series is provided in Figure 45 which shows the several interlocking communications (secure voice and data) loops among the various players in the exercise, from passive surveillance assets, to the ASWC, to the Theater Commander. Exercises organized like this, developed in direct coordination with the Fleet, established the benchmark for the introduction of LFAA assets into actual operations.

The end goal of LFAA C^4I and the cue-to-kill process is the effective placement of a weapon on the target. This last phase of the ASW problem involves the greatest number of interplatform-interface issues. In order to effectively pass control of the target in an LFAA environment, it is necessary to cue the weapon system platform onto the target. To achieve accurate targeting information, this platform must typically redetect the target, using a relocation sensor such as a dipping sonar or active sonobuoy. Such sensors are typically lightweight, often expendable, and high-frequency if active; and have limited detection ranges.

The cue-to-kill process often becomes time-sensitive, with the length of the delay in transferring targeting information between the original search sensor and the weapon system platform being critical. The controlling factors in this process are well described by the simple formula illustrated in Figure 46. Simply stated, the range of the relocation sensor from the target must be greater than the product of the target-evasion speed and the lag time in transferring the cued location.

Figure 46 Controlling Factors in the Cue-to-Kill Process

$R_{LOC} > V_{TGT} \times T_{LAG}$

$T_{LAG} = T_{PING} + T_{XFER} + T_{DEP}$, where:

T_{PING} = Search sensor ping cycle

T_{XFER} = Time to transfer the position data

T_{DEP} = Time to deploy and operate the relocation sensor

Values for example:

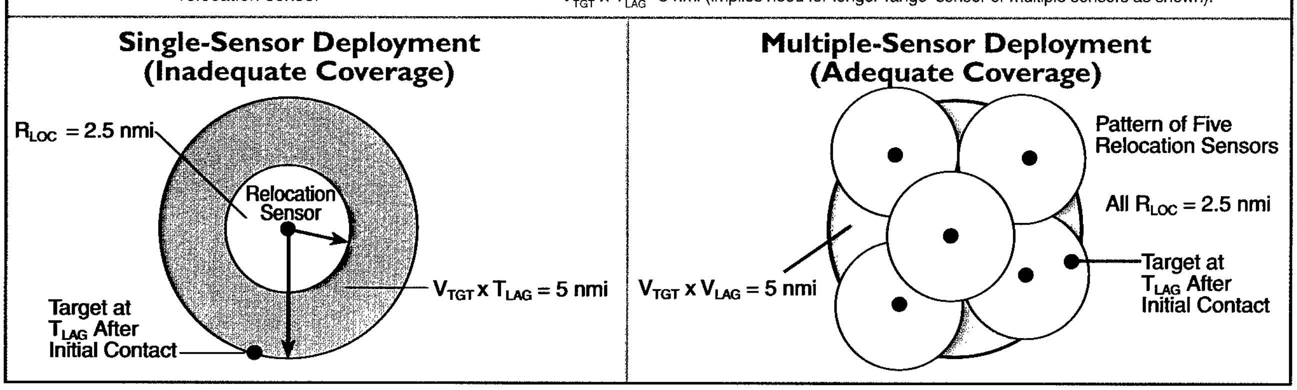
$R_{LOC} = 2.5$ nmi, $V_{TGT} = 10$ kt

$T_{PING} = 10$ min

$T_{XFER} = 10$ min => $T_{LAG} = 30$ min

$T_{DEP} = 10$ min

$V_{TGT} \times T_{LAG} = 5$ nmi (implies need for longer-range sensor or multiple sensors as shown).



LFAA Technology-Transfer and Fleet-Introduction Issues

As LFAA systems make their way into the Fleet, and as related concepts continue to be developed, it is the methods established in programs such as CST that will serve as the underlying technical bases for these systems in all areas, from Operational Concepts to baseline specifications for Tactical Decision Aids (TDAs). The lessons learned in each of these key issue areas are summarized and highlighted in Table 8. A more detailed exposition of each of these lessons learned can be found within the extensive documentation of CST and related programs (see Bibliography). It can also be found in the underlying bedrock of knowledge and expertise carried by the hundreds of persons, Fleet personnel, government program managers, laboratory scientists, and contractor personnel who participated in CST and its related test programs.

The transition from the meager level of understanding of LFAA USW applications that existed at the start of the CST Program through its evolution into now-almost-standard, highly developed procedures and practices, has been so thorough and dramatic that it is difficult to place it in perspective.

Table 8 Undersea Warfare Lessons Learned in CST

LFAA Technology-Transfer and Fleet-Introduction Issues	Lessons Learned
Operational Concepts	• Developed generic LFAA capabilities for all platform types: – Surface ships – Submarines – Aircraft – Fixed arrays(sonobuoys, etc.) • Established limitations in frequency and bandwidth as a function of sensor type and function: – Signal type – Processing methods • Developed Team USW approach: – LFAA threat characterization – Allocation of test assets – Enhanced search and classification – Threat localization and cue-to-kill • Used C^4I effectively • Defined data-fusion requirements • Explored application of deep-water LFAA USW capabilities to the littoral environment
Testing Requirements	• Capability to conduct real-time integrated operational/research testing: – Multi-sponsor tests – Multi-platform tests – Joint/international tests – Rapid-turnaround engineering and scientific assessments • Fully integrated secure communications and data flow from test planning phase to cue-to-kill
Training	• Developed training requirements in totally new areas: – Real-time EVA input to USW operations – Data-fusion operations – Team USW approach
Environmental Assessment (EVA)	• Developed and authenticated an entirely new family of EVA tools specialized for LFAA operations: – *In situ* measurements and updates to modeling of TL and reverberation – Integrated EVA and detection displays • Performed central EVA assessment and data transfer to multiple units • Performed major evaluation of all EVA tools and methods in littoral environments
Tactical Decision Aid (TDA)	• Established baseline requirements for TDAs at every layer of the USW problem, from Theater Command to individual units

Conclusion

This final CST summary report has offered highlights from ten years of contributions by the CST Program to the application of LFAA in Undersea Warfare. A continuing challenge during CST was the transition of products to the "user community." Throughout its history, CST has identified six mechanisms for this transition. First, each sea test was documented with a final report. Second, key technical results were distilled and documented in a series of white papers and technical reports. Third, the program closed with a final symposium, the proceedings of which constituted a key component of the program's overall final products. Fourth, raw data sets and archives were transitioned to users as appropriate. Fifth, the "hard" assets (projectors, processing equipments, etc.) were transitioned as appropriate. Sixth, and perhaps most important, the participants in the program have carried and will continue to carry the lessons learned in CST to other efforts in support of the Navy's Undersea Warfare development activities.

This report has discussed those various CST products from four perspectives. 1) The assets and measurement techniques developed by CST have become the standards for a variety of survey- and systems-development programs throughout the U. S. Navy. 2) The CST environmental acoustics investigations have not only directly supported upgrades of Fleet standard models and databases; they have also provided the baseline for system performance-prediction and analysis capabilities. 3) Investigations in signal and information processing have enhanced the capabilities of virtually every constituent of developing systems, from waveforms to signal and information processing, to adaptive processors, to performance-evaluation tools, to unique algorithms in support of fixed and air-deployed systems. Finally, 4) CST defined the necessary strategies for LFAA Undersea Warfare, including sensor-deployment strategies, quantification of gains associated with cooperative LFAA operations, and highlighting of overall communications and intersystem data-transfer requirements.

LFAA technologies have evolved in ways that were scarcely imaginable at the outset of CST. As often happens in technology research, every question answered has led to previously unimagined questions still to be answered. The future of LFAA still holds challenges at every level. LFAA operations in the littoral will continue to raise questions regarding basic physics and modeling of bottom-limited propagation and reverberation. Next-generation signal processing techniques, employing adaptive and model-driven processors, will continue to push the performance bounds of systems. New LFAA system concepts will develop to allow more efficient operation, whether via forward scatter triplines, reduced-energy multistatics, enhanced environmental matching, or other methods still to be formulated. The operational performance of LFAA systems will improve as tactics and supporting TDAs continue to evolve. As networks of interoperable LFAA systems mature, the communications, connectivity, and data-fusion trends initially developed by CST will reach their full potential.

The CST Program has been, and will remain, a key foundation stone for all of these efforts. CST has not only met its goal of supporting those LFAA systems that were under development during the course of CST; it has exceeded that goal by providing the bedrock upon which future developments will build.

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"Future Requirements in Performance Modeling"
"Lessons Learned Regarding Adaptive Beamformers"
"Coherent Interping Reverberation Suppression: System Applications"
"Survey of Classification Techniques for Impulsively Activated Sonar Systems with Applications to Extended Echo Ranging (EER) and Improved EER (IEER)"
"Integrated Signal/Information Processing and Performance Prediction"

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"Acoustic Warfare Summary Issues Report"
"Critical Parameters for Mission Planning"
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"Impact of CST Technology Transition on Navy Programs"

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"The Measurement of Sea-Surface Forward Scattering"
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